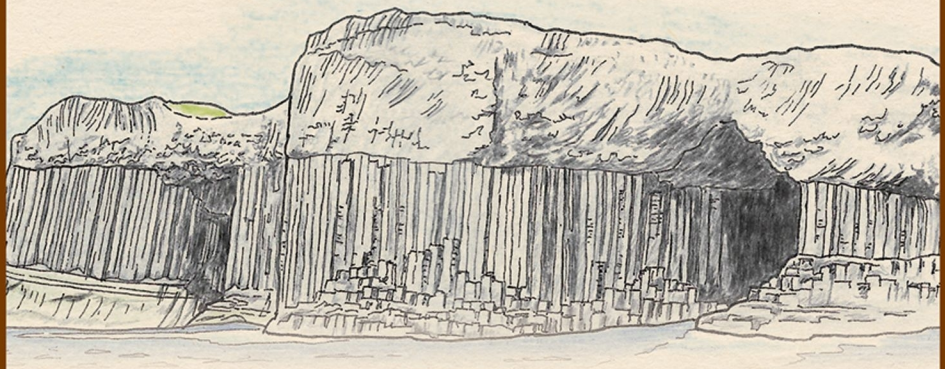
MATTHEW J. GENGE

GEOLOGICAL FIELD SKETCHES AND ILLUSTRATIONS

A Practical Guide



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Details make perfection, and perfection is not a detail—*Leonardo Da Vinci*

This book is dedicated to those who taught me, and those I have taught. In particular amongst my lecturers Paul Garrard, John Cosgrove, and Jack Nolan are thanked for their rigorous field training. The students I have taught are too numerous to mention, but those whom I know continue to espouse the value of drawing in fieldwork are closest to my heart.

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1

Introduction to drawing geology

Natural sciences are observational disciplines and in Earth Science, in particular, excellent observations are the key to rigorous interpretation. Often it has been through careful unbiased observations, rather than spontaneous ideas, that the greatest advancements in Earth Science have occurred. Conversely many of the greatest dead-ends in Earth Science have come about when observations have been overlooked or dismissed since they were not consistent with theory. Excellent observation and recordings are the first step in producing excellent science.

Observing the natural world is challenging since nature is often complex and can seem chaotic and random. Unravelling the chaos requires careful and systematic observation and description. The complexities of the natural world make it difficult to adequately describe in words all but the simplest outcrops of rocks, even when using the brevity of terminology. Pictures, in contrast, provide an excellent medium for recording the spatial variations that makes nature so intricate.

Drawing the structures and lithologies of rocks is a long-standing method of data collection in the field and is practised by all geologists at some stage in their careers. Field sketches are used to record spatially constrained information, whilst maps and cross-sections are used to illustrate the distributions and structures of units above and below ground. Schematic diagrams provide both an aid to interpretation and means of communicating geology to others. Effective use of pictorial representations of Earth Science processes can be transformative in pedagogy. Although drawing is a very useful skill in Earth Science, for students, professionals, and academics, little instruction is often given in the activity, apart from basic guidelines.

This book aims to provide an in-depth training in how and what to draw in Geology. It will introduce techniques that can be used to produce accurate sketches and diagrams as well as tactics to help geologists improve their drawing skills. Since knowing what features are most

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important to draw and emphasize in field diagrams is also important, this book is also a textbook in geology. The fundamental concepts of petrology, mineralogy, structural geology, palaeontology, and field techniques are all described in the context of drawing the features of rocks.

Although this is a book intended for earth scientists it also has useful tips for natural science students and amateur scientists in a wide range of disciplines, such as biology, geography, and environmental science. Any field of science that involves recording spatial relationships benefits from the ability to sketch. This is the book for those who want their notes look amazing as well as being full of technical detail. It is, be warned, no magic pill. Reading this book will not impart a magical ability to draw, but it will provide the tools and methods to draw with confidence, and with practice become an enthusiastic sketcher.

1.1 Why we draw geology

Teachers of Geology will often hear students say 'Why do I have to draw it? Can't I just take a photo?'—a lament that has become more and more common now that all of us carry devices with cameras with us all the time. Drawings, however, are crucial in making excellent field recordings because they are an aid to observation as well as a way of documenting what is seen. There is no substitute for a field sketch, since like the saying goes 'a picture is worth a thousand words'—although that very much depends on the picture. It is certain, however, that whatever the quality of the resulting sketch, taking the time to sit and draw a landscape or an outcrop of rock forces close observation of the most important features and will result in much more to interpret than if just a photograph is taken, as shown in Figure 1.1.

Diagrams are also an important part of communicating Earth Science to others. Effective use of pictorial representations of geology is valuable as a teaching tool. Enhanced graphics can produce a transformation of pedagogic value in the class-room or in the field. Pictorial learning aids are most effective for visual learners whom can envision imagery easily. For such people diagrams greatly assist in solidifying understanding. Even in the field, when individuals can touch and explore the rocks in front of them, diagrams drawn on a portable whiteboard demonstrate concepts much more clearly than words alone can convey. Photographs, even annotated on a tablet, do not have the same

Figure 1.1 Illustrating how field sketches can provide an enhanced means of recording geology compared to photographs. Showing a view of Ladram Bay in Devon.

impact. The ability to draw is thus just as important for lecturers, as it is for students.

Photographs are nevertheless very useful in field geology and many of them should be taken. There is, however, a tendency with photographs to snap and move on, hardly paying attention to what is being imaged, let alone where the photograph was taken, and in what direction. Photographs of rocks are often also very difficult to interpret. Firstly,

they are in two dimensions, a single view from a single perspective. A sudden change in the orientation of a feature such as a bed of rock could be a fold, or it could be a planar bed seen on a curved surface. When sat in front of the rocks it is easy to move and see which it is. A single photograph doesn't record that three-dimensional (3D) information.

Many academics are now working with aerial drones to generate 3D models of outcrops and landscapes. These are highly useful means of recording the geometries of geological structures; however, they do not encourage careful observation in the field, instead demoting it to a post-field, data-processing, activity. The 3D models of drones also suffer from the same resolution issue as photographs. A single pixel may be 2 cm across, and all the fine-scale information has gone.

Another difficulty with photographs or drone imagery is with colour. The human eye is very sensitive to subtle differences in colour. Often geologists will talk about the colours of rocks as if they are obvious, such as the 'pink rhyolite' and the 'blue andesite', when in fact they are very subtle, more a grey-pink and a grey-blue. In a photograph they are likely to look all the same dull grey colour. Telling the difference between rock types is difficult enough in the field with the aid of a hammer and a hand-lens. It is often not possible from a photograph.

Illumination is also a significant problem in the interpretation of photographs. Our brains are very good at filtering images, thus we can see beyond differences in illumination and trace a feature from brightly lit areas into the shadows. In photographs shadows become deeper, particularly in bright sunshine, and seeing features becomes almost impossible. There is unlikely to be a single geologist who hasn't taken picture of an outcrop, and later wondered why they took it. Photographs make the most imperfect way of recording geology. Therefore we draw.

1.2 Illustration in Natural Science

Pictures have been used to illustrate concepts and provide a visual explanation of text throughout history. In fact, pictures predate writing by a significant period of time and it is likely that they actually predate language. Communication through images is so fundamental that when it finally came to recording language letters evolved from pictographic representations of words.

The modern tradition of illustrated books arguably began with the iconography of medieval religious texts. Ornate and richly coloured

illuminations were hand drawn and painted and the best examples, such as the Book of Kells, held within Trinity College Dublin, are in themselves works of art. Although these illustrations were not technical in nature they provide a context for the scientific illustration that later developed since they were designed to emphasize the information held in text. They demonstrated that pictures have an additional explanatory power that words alone could not convey.

The first scientific illustrations within books came in the sixteenth century with the advent of printing technology that could produce large numbers of copies without laborious and slow illustration by hand. Perhaps the first example of geological illustrations were those of fossils, since these petrified creatures were a peculiar natural oddity that attracted wide interest in the fledgling world of natural science. Diagrams of fossils were included by Conrad Gesner (1516–1565) in his work '*De Rerum Fossilium*', published in 1565. Gesner used diagrams to demonstrate the similarities between modern and fossilized creatures. Thus scientific illustration was born out of the need to prove a controversial hypothesis, that fossils were once alive and are organisms transformed to stone. 'Seeing is believing' is thus a cornerstone of scientific illustration.

In Figure 1.2, an illustration from '*De Rerum Fossilium*' shows the morphology of an echinoid. The drawings are of a remarkable quality considering they were printed by woodcut. They resemble modern line drawings and are accurate simplified representations of the main features of echinoids showing the pentaradial symmetry, the ambulacra with spine attachments, and the interambulacra areas. Gesner uses different line widths within the drawings to emphasize features, a technique that will be used throughout this book. He also uses shading to impress volume upon the reader, which is a sophisticated technique that can be difficult to achieve well.

Although Gesner's book provides the first published illustrations of this type, there were earlier representations of geology. German scholar Georgius Agricola (1494–1555) included illustrations to show the locations of mineral deposits in his book '*De Re Metallica*', published in 1556. The diagrams, such as that shown in Figure 1.3, however, were schematic by comparison with those of Gesner and clearly were not drawn as sketches of real objects, but as exaggerated illustrations. In particular features are not draw to scale. Shading and differing line with, however, is used to provide an illusion of depth. The exaggeration is typical of

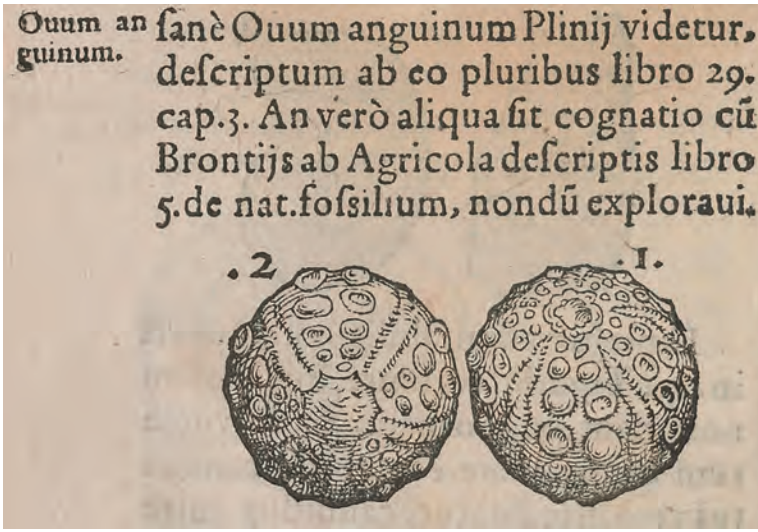

Figure 1.2 Illustration of an echinoid in Conrad Gesner's *De Rerum Fossilium*.

Figure 1.3 An illustration of ore deposits in Giorgios Agricola's *De Re Metallica*.

early renaissance illustrations and similar examples can be seen in '*Mundus Subterraneus*' by Athanasius Kirchur (1602–1680) published in 1665.

Evidence exists that natural scientists had made use of drawing in recording observations before their appearance in print. The Italian polymath Leonardo da Vinci (1453–1519) kept detailed notes (his Codex) that were full of detailed sketches and diagrams—used principally to record observations that were too complex to be sufficiently described in words. In addition to anatomy, cartography, mathematics, and engineering, Leonardo da Vinci had a keen interest in geology, perhaps born out of his landscape painting. His drawing of a Tuscany landscape (Figure 1.4, dated 1473) shows his attention to detail and appreciation of realistic perspective, which was unusual amongst his contemporary artists. In particular in this sketch da Vinci includes realistic bedding in the sedimentary rocks near the waterfall that emphasizes the lower bedding planes. These are probably turbidite packets with erosional lower contacts. Although not a geological sketch as such, since the geological features are not the subject, it does illustrate many of the principles of a good geological sketch that will be discussed later in the book.

Figure 1.4 The Arno Valley by Leonardo da Vinci (1473).

Considering his fame as an artist, Leonardo da Vinci doesn't provide an ideal example of a field sketch achievable by most people. However, not all his sketches were as detailed or as accurate. In folia 25r of his codex I, he includes sketches of fossils brought to him by peasants whilst he was working in Milan probably around 1499 (Figure 1.5). These clearly show brachiopods and the trace fossil paleodictyon; however, they are rough drawings with some issues with symmetry and accuracy. Even da Vinci it seems would sometimes sketch objects quickly as a reminder of their form but without adequate detail.

A specific focus on drawing natural objects in order to make more accurate and detailed observations was championed by Italian naturalist Ulisse Aldrovandi (1522–1602). In his posthumous work '*Museaeum Metallicum*', published in 1648 he says:

to understand plants and animals there is no better way than to depict them from life

Figure 1.5 A reproduction of Leonardo da Vinci's sketch of fossils from *Codex Leicester Hammer*.

The concept of drawing nature as a means of study, rather than just as a way of illustration, was also championed by Italian botanist and geologist Fredrico Angelo Cesi (1585–1630). Cesi founded the Accademia dei Lincei (the Academy of the Lynx) in 1602, a scientific academy based in Rome dedicated to scientific investigation free from political or religious control—a dangerous endeavour next door to the Vatican. The academy was named after the cover illustration on the book '*Magia naturalis*' (1558) by Giambattista della Porta (1535–1615), who had established a similar academy in Naples, which showed a Lynx with the words:

> *. . . with lynx like eyes, examining those things which manifest themselves, so that having observed them, he may zealously use them*

The academy encouraged its members to record the natural world in pictorial representations and accumulated over 7000 drawings and paintings of natural objects, landscapes and phenomena.

The first verifiable sketches of geology made in the field can be attributed to Fredrico Cesi. His work was of sufficient quality to be used after his death in 1637 in Francesco Stelluti's (1577–1652) book on fossilized wood '*Trattato Del Legno Fossile Minerale Nuouamente Scoperto*'. Cesi's sketches were used by Stelluti to construct a locality diagrams in his book, as shown in Figure 1.6. Stelluti's book also included many hand specimen

Figure 1.6 Fossil wood locality at Rosaro in Italy.

images of fossil wood that are also high quality and the first microscope images to appear in print.

Geological illustration became increasingly used through the eighteenth century. Scottish geologist James Hutton (1726–1797), who established some of the most important principles of geology, demonstrated his theory of plutonism using a geological map of Glen Tilt in Scotland. A map by John MacCulloch of Glen Tilt published in 1815 and incorporated in to later editions of Hutton's book *Theory of the Earth* is shown in Figure 1.7. The map demonstrates how observations recorded in the field allow complex information to be conveyed and interpreted. These sketch maps will be considered later in this book.

Hutton also used sketches collected in the field to record and interpret geology. He included many drawings in *The Theory of the Earth*. The drawing of the unconformity at Jedburgh in Scotland shown in

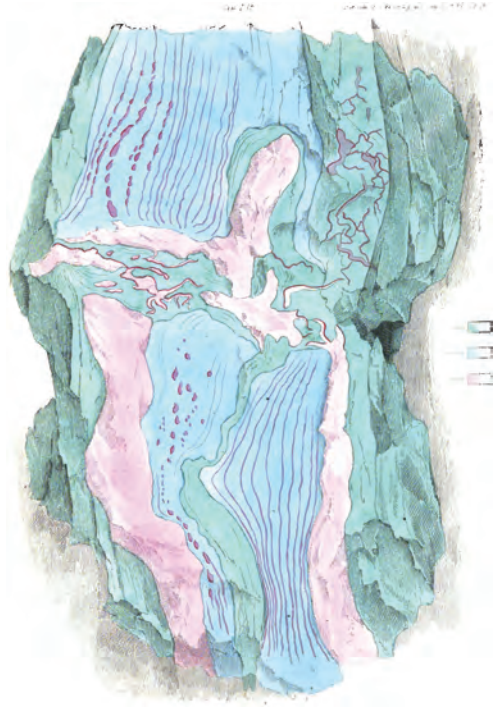

Figure 1.7 John MacCulloch's map of Glen Tilt published in 1815 in the *Transactions of the Geological Society*, volume iii.

Figure 1.8 was used to demonstrate the concept of geological time and was based on field observations.

Hutton employed an artist, John Clerk to accompany him in the field to record the geology. The same artist produced impressive hand specimen diagrams for Hutton's book such as a sketch of a granophyre (Figure 1.9). This diagram provides a high level of detail that illustrates very well the nature of the graphic texture, showing the intergrowth of alkali feldspar and quartz. Part of the reason for the sketch is to allow others to recognize similar samples, and in this respect the diagram achieves its aim. Such detailed illustrations, however, are rarely feasible in the field and best created afterwards. Today a photograph would provide a more than adequate recording of such a specimen.

Hutton also used cross-sections to extend geological relations into the subterranean realm. His cross-section of the isle of Arran, showing its central intrusion deforming the surrounding Dalradian and onlapping later Devonian strata, is an excellent early example of this type of diagram (Figure 1.10). In a later section in this book the creation of sketch cross-sections will be described as a semi-schematic means of interpreting the spatial relationships of between geological units.

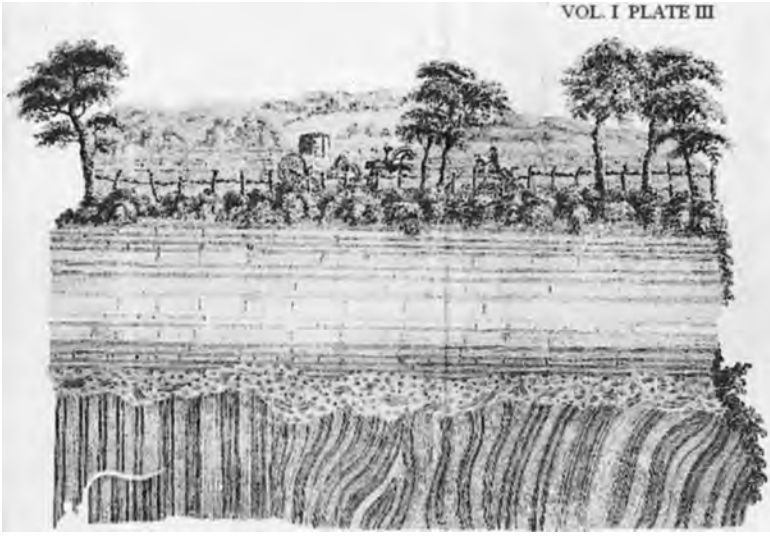

Figure 1.8 An illustration of Hutton's unconformity at Jedburgh in Scotland for his book *Theory of the Earth*.

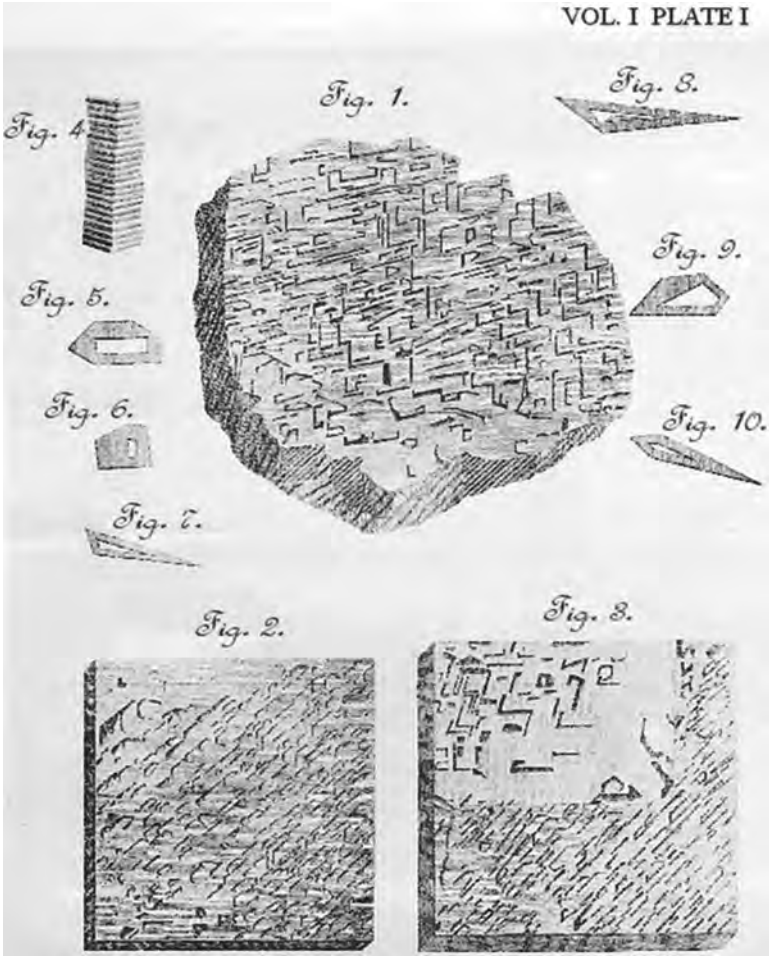

Figure 1.9 Graphic granite from Hutton's *Theory of the Earth.*

Improvements in printing technology, with the development of the chemolithograph in the 1790s, allowed reproduction of colourful detailed images. Increasingly geological illustrations became more elaborate with finer drafting lines and realistic colours. Illustrations of fossils within William Smith's (1769–1839) monograph entitled '*Strata Identified by Organized Fossils*' published in 1816 made full use of these developments and played a crucial role in popularizing his methods amongst

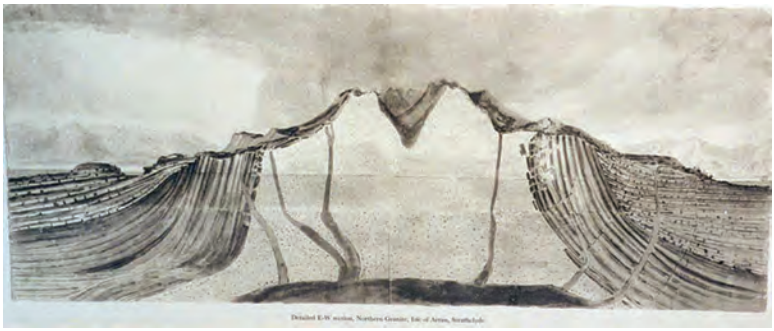

Figure 1.10 Cross-section of Goat's Fell on the Isle of Arran by James Hutton (Credit: U.S. Geological Survey, Department of the Interior/USGS).

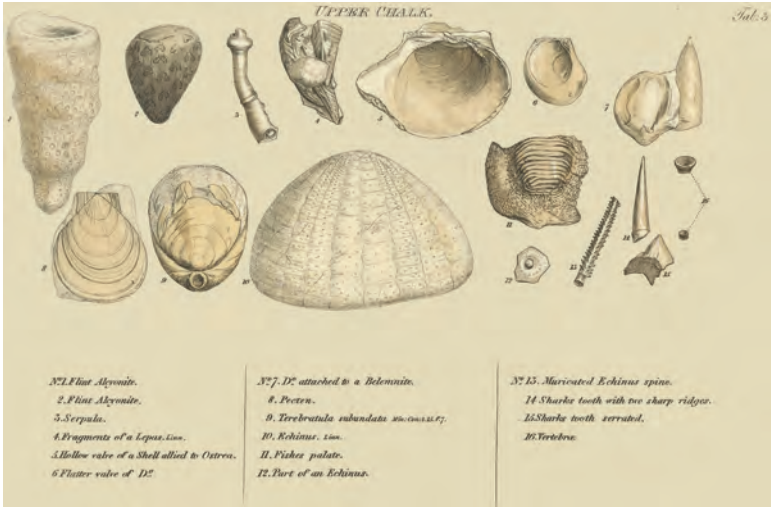
UPPER CHALK.
Tab. 5
N°1. Flint Alcyonite.
2. Flint Alcyonite.
3. Serpula.
4. Fragments of a Lepas. Lin.
5. Hollow valve of a Shell allied to Ostrea.
6 Flatter valve of D°
N°7. D° attached to a Belemnite.
8. Pecten.
9. Terebratula rubundata
10. Echinus. Lin.
11. Fishes palate.
12. Part of an Echinus.
N° 13. Muricated Echinus spine.
14 Sharks tooth with two sharp ridges.
15 Sharks tooth serrated.
16 Vertebræ.

Figure 1.11 Fossils from the upper chalk from William Smith's monograph *Stata Identified by Organized Fossils* published in 1816.

other geologists. Smith maintained that particular stratum contained specific fossils that differed from other layers allowing them to be identified. The detailed illustrations (Figure 1.11) enabled other geologists to test and confirm his findings, establishing new important tools in stratigraphy. These concepts would be later be crucial in the discovery of the theory of evolution.

The new printing techniques also coincided with the publication of Smith's famous geological map of the United Kingdom—the first large-scale, national map of geology (Figure 1.12). Its publication revolutionized Earth Science and propelled it into the industrial era. Using Smith's stratigraphic techniques, together with those already established by Hutton, the geology could be traced across the landscape. The application of geology as a natural science to mining, civil engineering and agriculture became apparent just at the time when the industrial revolution was beginning.

Perhaps the zenith in geological illustration came when the boundary between utilitarian diagrams and art became blurred. Sketches by the naturalist Richard Waller (d. 1715) of Robert Hooke's collections of fossils published in '*Posthumous Works*' in 1705 are clearly designed with an aesthetic empiricism in mind. The sketch shown in Figure 1.13 illustrates 'snake-stones', now termed ammonites, which Hooke proposed

Figure 1.12 William Smith's 1819 map of Sussex.

Figure 1.13 Illustrations of snake stones by Richard Waller published in Robert Hooke's 'posthumous works', 1705 (Credit: Wellcome Collection).

were the petrified remains of ancient creatures. The sketches convey the taxonomic characteristics of ammonites but are also beautiful pieces of art. Elements such as the shadows cast by specimens, which partially obscure parts of the annotation, would not normally be

included in geological sketches, but in this case provide the specimens with the impression of volume. Such realism in art is suited to science since it represents the subject without artefact and stylistic convention. This contrasts strongly with the conventional art world of early eighteenth century that was dominated by the exaggerated and grandiose Baroque movement.

The advent of new scientific techniques has influenced the nature of geological drawings. In Earth Science the development of polarizing microscopy and thin-section preparation was momentous. For the first time it was possible to see a whole new world of petrology at microscopic scales and to identify minerals with little uncertainty. The new technique demanded a new type of illustration.

The petrographic microscope first became possible in 1828 when Scottish physicist William Nicol (1770–1851) discovered that polarized light could be generated by passing light through a crystal of Iceland spar, a variety of calcite. At first only individual mineral grains could be observed with such microscopes, however, in the 1840s the preparation of optically thin-slices of rocks through polishing was developed and the petrology of entire specimens could be recorded. Illustration techniques adapted to this two-dimensional world.

Some particularly interesting examples of sketches of petrology in thin-section were used by Prof John Wesley Judd (1840–1916), from the Royal School of Mines, within '*The eruption of Krakatoa and subsequent phenomena*' published in 1888 by the Royal Society. The samples comprised of pumice ejected in the 1883 eruption of Krakatau and lavas collected on the island. The diagrams illustrate that a degree of simplification best gives optimal results, since in thin-section the detail can overwhelm the important elements of the petrology. Using these techniques Judd demonstrated that the Krakatau pumice changed in character from the beginning of the eruption to its intense climax. He showed that the pumice records the flow of magma and the all-important formation of vesicles in abundant glass with relatively few crystals present. He also examined samples of older lavas present on the island and these thin-sections are shown here in beautifully detailed images (Figure 1.14).

With the development of photography in the late nineteenth century, illustration through drawing began to decline in its role as a means of presenting evidence in geological research. Geologists, however, continued to draw in the field as an aid to interpretation. Schematic diagrams also became popular in textbooks to demonstrate concepts,

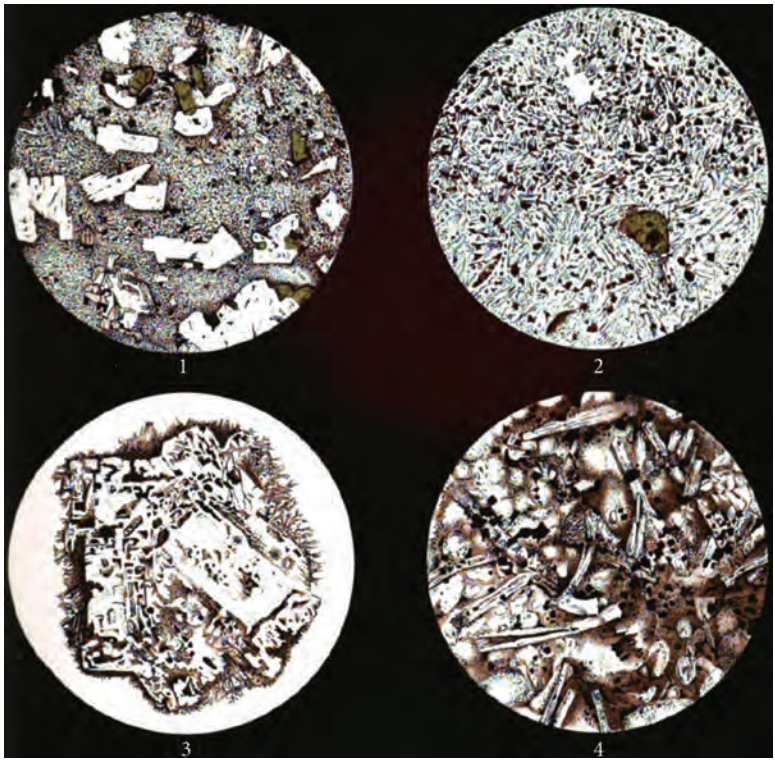

Figure 1.14 Thin-section diagrams of lavas from Krakatau from the Royal Society Report on Krakatau, 1888.

and in the field to guide the process of interpretation. Certain schematic diagrams, such as the sedimentary log, however, have more technical uses in the recording of scientific information and remain widely used. Schematic diagrams are also included throughout this book as a means of illustrating the spatial relationships of geological structures and the terminology that describes them. These diagrams are often more difficult to draw than field sketches since their subjects stem from the imagination and their perspective must be constructed rather than observed.

Today many professional geologists do not draw in the field and rely on the imperfect medium of the photograph to record geology. The opinion that sketching is an activity that is not worth the time, unless you are sufficiently 'artistic', is widespread. The history of geological

illustration, with its focus on famous artists and those geologists of legendary reputation perhaps dissuades those who are not confident of their abilities. A geological sketch, however, is not art and its aesthetic qualities are not important. It is the ability of a geological sketch to record information that defines its quality.

1.3 Everyone can draw

The commonest explanation for not wanting to create a sketch of an outcrop is 'I can't draw'—it is also not true, everyone can draw. What people mean when they say they cannot draw, is they can't draw as well as those they consider 'artistically gifted'. However, most people can draw a stick person to approximately the same level of proficiency. Of course, the stick person is easy to draw well because it is so simple, and there's not really any way for the 'artistic' person to do any better than the 'I can't draw' person. This does show a very important point. We are all capable of drawing simplified sketches of familiar objects at a minimum level of competency.

Often people who can draw pictures are considered as 'naturally talented'. The implication is that being able to draw is a talent people are born with, something genetic, such as height or hair-colour. This is, however, not exactly true. No one has the immediate ability to draw, it is a learnt ability, albeit one most natural to those with the best hand to eye coordination. The reason that some people seem to be able to draw and others not is mainly the result of practice. At some point most people give up drawing and do something else they find more rewarding. The point is those who keep drawing, have far more practice than those who stopped.

There is a general rule of competence in anything, the more the activity is practised, the better we become at it. To be an expert in something, whether it is playing the trombone, woodwork or cooking, around 10,000 hours of practice is required to be an expert. The 'artistic' person has been drawing all their life, they've practised and perfected their technique, so it seems like they can naturally draw, but their inherent ability may not be much more than anyone else. Everyone, of course, has a plateau of ability in any particular activity; the objective is to reach it.

It is not necessary practice for 10,000 hours to draw, a few hundred will suffice to become good, and after maybe 40 hours of practice a

significant improvement will be noticed. The reason is, those who have practised drawing, by and large, have never been taught to draw, they learnt through trial and error what works and what doesn't, and they've also got into some bad habits that can make their sketches less valuable. Most artistic people don't consciously use any of the techniques described in this book, but subconsciously they'll be using similar techniques to those taught in the following chapters.

1.4 What you'll learn

Learning how to draw geology involves an understanding of drawing techniques and the tactics that can be applied to different types of geology. An appreciation of what are the most important features to draw and their interpretation is also required both for drawing and the annotation of diagrams, thus a good background in the fundamental principles of geology is required.

The following chapters will explain how to produce accurate sketches through establishing their scale and aspect ratio from the outset and through correct positioning of elements of the drawing using guidelines and references. Various methods to position details correctly are discussed since these vary with the type of sketch. The use of different line styles is also shown to be particularly important in producing realistic drawings.

Post-drawing tasks are also described in this book. Colouring-in diagrams can considerably enhance their value and is a particularly useful means of emphasizing lithological differences. The application of base colours and more advanced shading and texturing techniques are described to allow high quality sketches to be produced.

Many of the basics of drawing techniques are described in Chapter 2, including three rules that are always applied when embarking on a field sketch. The rules ensure a sketch will provide the maximum possible scientific value. Later chapters focus on drawing specific types of geology and include faults and folds (Chapters 3–5), igneous rocks (Chapter 8), and sedimentary outcrops (Chapter 9). Metamorphic rocks are discussed, along with the complex folds they contain, in Chapter 5. The thought process involved in drawing simple outcrops is described in detail in Chapter 3.

Methods to draw different types and views of objects are also described. Drawings of fossils are discussed in Chapter 10, whilst those

of hand-specimens and thin-sections in Chapters 11 and 12. These diagrams are all different in character to field sketches and require different approaches. Drawings of rocks in three-dimensions and in landscapes are described separately in Chapters 6 and 7 since these sketches can be particularly challenging.

Each chapter in this book also includes background information on the science within the sketches. Understanding the fundamental principles of the geology is not just crucial in the interpretation of drawings and their annotation, but also in identifying what features should be drawn. This book is, therefore, a textbook in Geology to first and second year undergraduate level, although more experienced geologists will also find this information useful as a reminder. Throughout the book large numbers of worked examples of sketches are included, giving a step-by-step illustration of how to construct drawings. The sketches include description of interpretation and thus also help to develop understanding of geology. Common mistakes made in drawing are also shown in most chapters.

Although field sketches are the principle subject of this book, maps and cross-sections are also crucially important diagrams in recording and understanding geology. The techniques used in creating maps and cross-sections are described in Chapters 13 and 14 and focus on sketch maps and sections that can be used in notebooks to assist interpretation.

Schematic diagrams, such as block diagrams, are highly useful in developing ideas on the interpretation of geology and in illustrating Earth Science to others in lectures, reports and papers. Methods to construct schematic diagrams and the types of diagram to use are described in Chapter 15.

Finally, Chapter 16 describes modern methods in data recording and illustration in geology. It describes how to create 3D models of outcrops and how to prepare publication ready figures and illustrations for scientific reports and papers.

2

The methods of drawing

Drawing is not difficult; however, there are some elementary skills that need to be developed to draw accurately and quickly. People who have drawn regularly are likely to already have these skills, but those who rarely draw are likely to lack the hand–eye coordination required to produce good sketches and thus require practice. Further techniques are also required for the drawing of the natural world and these will not be familiar even to those who are artistic. All need to be learnt and, just as important, practised.

This chapter describes basic skills in general drawing as well as techniques that are specific to drawing geology. The first sections of the chapter give advice for those who struggle to draw to improve their basic skills and provide exercises to allow them to improve without significant effort or time expenditure. Even those who are artistic will find this advice useful. The latter parts of the chapter describe specific skills required to draw natural objects to scale and include three important rules to follow in any geological sketch. A recommended list of equipment needed for drawing field sketches is also given.

2.1 How to hold a pencil

It sounds ridiculous but not everyone holds a pencil correctly. A pencil should be pinched between the forefinger and the thumb, as shown in Figure 2.1. Some people wrap their forefinger around the pencil and hold it against their index finger; however, this doesn't give the same amount of accuracy in position. Occasionally people hold a pencil like a dagger. Grip the pencil firmly but lightly. Rest your wrist on the paper whilst drawing, rather than holding your hand above the page—this will stabilize your hand, making it easier to be accurate. The pencil lead should only lightly touch the paper sufficiently to make a mark. It is a common mistake to push too hard onto the page. If you have been holding your pencil incorrectly, then you'll need to

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Figure 2.1 How to hold a pencil.

practice holding it properly. It won't come easy and can take 20 days to become habitual.

2.2 Drawing simple shapes

Legend has it that the ability of an artist can be judged by their ability to draw a perfect circle—a belief that stems from the artist and scientist Giotto who drew a circle for Pope Boneface VIII to prove his expertise. Although drawing a perfect circle is only a test of how well you draw circles, drawing simple shapes is a useful exercise in hand–eye coordination and develops muscle memory that allows shapes to be drawn automatically.

Several different shapes are useful to draw repeatedly as an exercise. Squares and rectangles develop the ability to draw parallel lines and to draw to scale. Drawing squares with equal length sides and ninety-degree corners develops accuracy. Varying the size of squares, so that some are two or three times the size of others, reinforces the ability to draw to scale. Parallelograms and triangles are also useful to draw, in

particular, drawing specific angles and lengths will help with the accuracy of movements with a pencil. This exercise should be repeated over an extended period of a few weeks. It doesn't, however, require much in the way of concentration and can be achieved whilst watching or listening to something else to relieve the boredom. Essentially the exercise is to doodle continually.

Circles and ellipses are also important shapes to draw, although it isn't necessary to draw a perfect circle, since, except for planetary bodies, these are rare in nature. The most crucial aspect of drawing circles and ellipses is to generate a smooth curve. A useful technique in drawing larger curves is to rotate your wrist sideways whilst holding the pencil on the page. It is in fact easier to draw a large curve than a perfect straight line since the human body has joints designed to rotate and only a single joint is involved in drawing a curve, whilst many must be used in unison to draw a straight line. For smaller circles a coordinated motion of the thumb and index finger with little movement of the hand is required.

In drawing enclosed curves an important ability is to ensure that the pencil line ends up back at the same place it started and that the orientation of the line matches the starting direction—otherwise a teardrop or heart shape is produced. Doodling circles and ellipses will improve your ability to draw smooth curves to scale which will prove important when adding details to sketches of sedimentary rocks and fossils.

2.3 Drawing complex shapes using guidelines

Drawing complex shapes with irregular outlines is difficult to achieve without a framework to use as a guide. Artists often use a technique to draw complex objects that involves creating the geometry by combining numerous smaller simple shapes. To draw a person, for example, an artist will draw the head, neck, upper torso, lower torso, etc. as separate ellipses with set relative sizes dictated by human anatomy. These simple shapes are much easier to draw than the outline of a human body, and thus easier to draw to scale. The resulting combination of simple shapes can then be used as a rough guide, by which the detailed outline of the person can be drawn, adding those small details such as ears, fingers, and thumbs that make humans difficult to draw. This approach to sketching is shown in Figure 2.2.

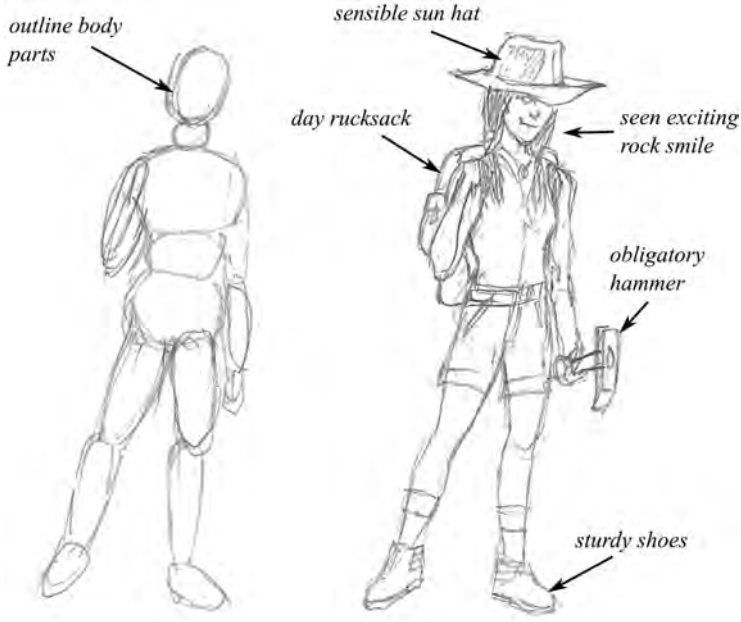

Figure 2.2 Using guidelines to draw a person (a geologist).

Whilst humans, animals, and plants can often be simplified down to a series of stacked ellipses, rocks and landscapes often can be simplified to a series of straight or curves lines. Drawing an outline of a cliff or crag, or the horizon of a landscape, as series of straight lines to use as a guide for the addition of detailed features is a technique that will be used throughout this book. Like all techniques it requires practice to be able to simplify a complex object down to a set of simple lines. Practising this technique is important to develop competency and speed. Images obtained online provide an endless resource on which to practise, as shown in Figure 2.3.

In drawings with many objects, the positioning of elements relative to each other is crucially important in accurate representation. A technique to ensure objects are placed in the correct position on the page, and have the right size, uses a quadrant grid. The position of objects within a field of view can be estimated according a set of approximate coordinates, for example, halfway down the upper right quadrant, one quarter the way across the right quadrant. This technique

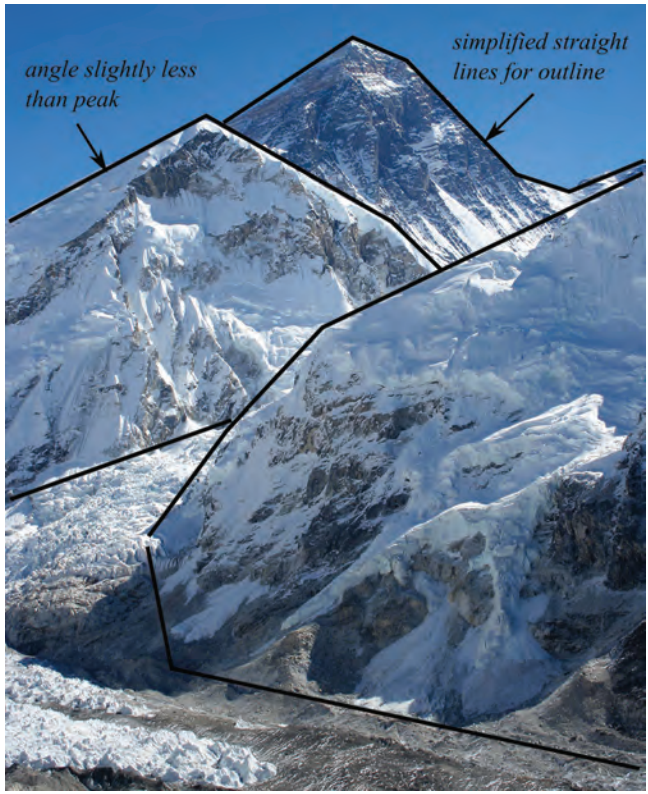

Figure 2.3 A simplified outline of a view of Mount Everest (photo credit: Pavel Novak).

can be used to position the most important features in a drawing, rather than all the features, since it is slow to apply. At first using a quadrant system will feel very unnatural and laborious; in particular it requires imagining the centre and borderlines of the drawing on the view in front of the eyes. With some practice, however, the technique will become instinctive. It also reinforces the correct thought processes during drawing, which continually questions the positions of features relative to the drawing area and other objects in the image. An example of how the quadrant system can be applied is shown in Figure 2.4.

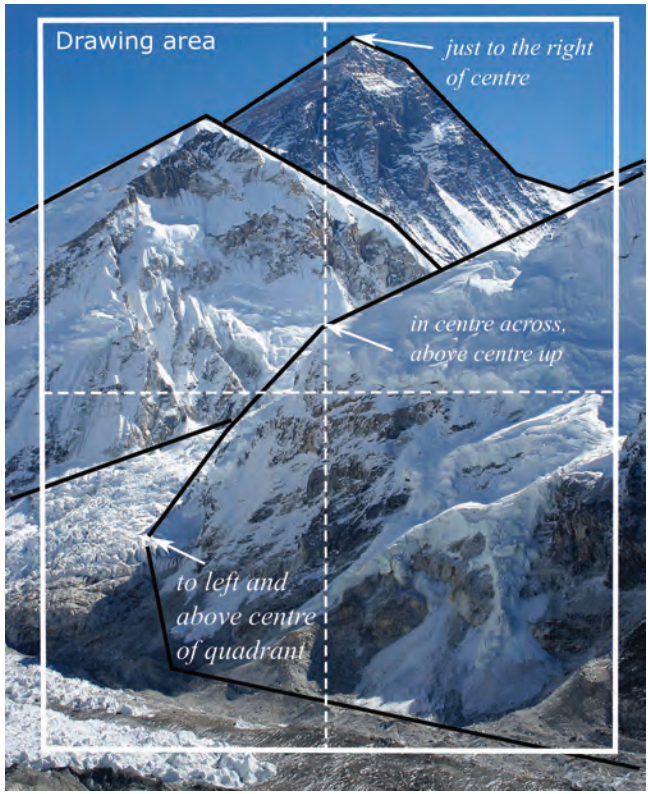

Figure 2.4 Using a quadrant grid in the drawing area to generate approximate coordinates to position features (photo credit: Pavel Novak).

2.4 Biomechanics, memory, and drawing

Drawing involves coordinating the motions of the hand according to what the eye can see. The processes involves interpreting the visual image to identify the lines and curves that need to be drawn, and deciding what movements are required to produce the line on the page. Identifying the features to be drawn is a conscious act and involves constant questioning on the position and importance of lines. The procedure involves assessing the simplifications needed in the initial stage of drawing and evaluating the details that need to be incorporated later in the sketch. Excellent observation is crucial in producing good field

sketches and a detailed example of the thought process involved is given in Chapter 3.

Determining the movements required to produce lines in a drawing is largely autonomic. Just as walking or running do not require conscious thought on which joints to move in what sequence, drawing a circle should need no conscious thought other than 'where does the circle start?' and 'how large is the circle?'. Walking and running are, however, activities that almost everyone learnt to do through trial and error at an early age—proficiency in drawing likewise needs practice to become automatic.

Movements used in drawing are complex since they involve coordination between numerous muscles with a precision of less than a millimetre. It is the precision of the movements and the number of muscles involved that makes drawing difficult. Other activities, such as playing the violin, however, likewise involve very precise complex movements. With practice a violinist need no longer consciously think about the position of their fingers on the strings. Muscle memory ensures the movements can be achieved with precision without conscious thought and is produced by motor learning—an association of motor neurons in the cerebellum and basal ganglia of the brain. Motor learning is developed through practice, or rather experience, and takes time. In drawing, conscious decisions on movement are needed by those who are inexperienced, but as motor learning develops, the accuracy of movements will become instinctive and the speed of drawing will increase.

Biomechanics is also important in good drawing practice. Some of our joints have limited motion in some directions making some movements difficult when in an awkward position. Adjusting stance often makes a movement is easier to achieve. Good posture makes drawing easier.

The ideal posture for drawing is to rest the wrist on the page to support the arm. The paper should not be too close or too far away to enable a comfortable arm position. Ideally the page should be angled towards the artist, so it is as near as possible to perpendicular to the line of sight when looking at the page. This arrangement will minimize the effects of perspective.

Another important factor influencing drawing posture is the nature of short-term memory. Humans have an active memory that can store information for a few seconds. The probability of accurate recall decays

with time since the neurotransmitters that make up the memory trace are automatically reset to free up memory space. Information such as the positions of lines and curves in a visual image, therefore, are best accessed in the shortest possible time. Positioning the page close to the field of view allows the eyes to be moved quickly from the subject to the page, which deceases the required retention time for the visual image and thus improves the accuracy of the sketch. A position where a notebook is held high and just below the field of view is thus better than a position where a notebook is low and needs the head to be moved. Adjusting your head whilst drawing slows the drawing process since it causes momentary disorientation.

The constraints of short-term memory lead to the common mistake of trying to draw whilst holding up a notebook with one hand whilst drawing on the page with the other. This posture, however, is sub-optimal since the notebook will not remain in the same position. Standing up whilst holding a notebook also can become tiring after many field sketches. The ideal posture for drawing is to sit down whilst leaning against an object, such as a rucksack, rock or mapping partner, with legs up and the notebook resting on the knees. If wet ground or obstructions to the view make sitting down difficult, a notebook can be rested on an object such as a wall or rock to obtain the best possible position. A comfortable posture will result in a remarkable improvement in the quality of a drawing.

2.5 Drawing style and the clarity of lines

Where illustration and art differ is in style. An artistic work can have a distinctive style, whilst an illustration tends to be a simplification of reality that is largely true in form and scale to the subject, but may emphasize certain features of interest. Line style in particular is an important distinction between illustrative and artistic drawing. In illustrations lines tend to be carefully drawn and precise with a simple line style. Variations in line width can be used for emphasis, but the thickness of individual lines is kept constant and clean. Illustration is the most purposeful form of artistic expression, as shown in Figure 2.5. Every line in an illustration has a reason and relates to the observed subject. In artistic drawings lines can vary in thickness for effect. A common mistake in field drawings is to make scratchy artistic lines by rapidly moving the pencil back and forth across the page; however, this technique leads to inaccuracy.

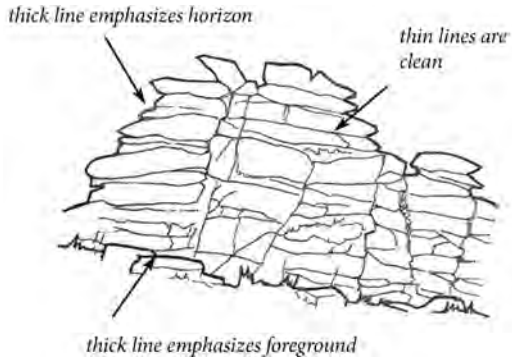

Figure 2.5 Illustrating the line styles used in geological sketches. Lines should be clean; however, line width can be used for emphasis.

Although simple lines are used in drawing geology they do not need to be continuous. Often features such as laminations or cleavages are subtle and cannot be followed far along their length. Discontinuous lines can be used to illustrate such less prominent features and should have stroke lengths that reflect the scale of the objects observed. Regular dashed lines should not be used to draw subtle features and are best reserved for annotations and interpretations, such as extrapolated boundaries.

2.6 The importance of scale

Scale is fundamental to the accuracy of drawings of geology. A geologist should be able to judge scale and distance at a glance and this requires practice. Regular exercises in estimating the size of objects is, thus, useful. Relative scale, in particular, is important. The width to height ratio of the exposures being drawn is often crucial in beginning a sketch and is most easily achieved by holding up a pencil at arm's length and measuring how many pencils wide and how many pencils across the field of view extends. It is most common to accidently exaggerate the height of an exposure or landscape. Errors in the aspect ratio of drawings tend to compound and lead to great difficulties in positioning small scale features relative to each other.

All sketches also need a numeric scale added as a labelled bar. Often a colleague is a useful means of estimating scale, in particular if they happen to be 2 m tall. Counting the number of people that would need

to be stacked to reach the top of a cliff is also a useful means of measuring the height of larger exposures—although this should be achieved without actually stacking people. For landscapes, a map provides a useful way of cheating; otherwise trees and buildings provide some means of estimating the height of hills and mountains. For small objects a notebook or hammer of a known size is useful as a makeshift ruler, although not as useful as a real ruler.

2.7 The rules of geological sketching

There are three rules that should be used in creating a field sketch, including those to apply before even making the first mark on the page of a field notebook.

2.7.1 Rule 1—look first, then draw

A common mistake when drawing an outcrop is to immediately start sketching without first looking at the outcrop. This does not mean that it is necessary to go over to the outcrop and make detailed observations. It is necessary, however, to first evaluate what are the most important features to be drawn. Essentially, look first to decide whether it is necessary to draw the outcrop. Sometimes, actually quite often, there is no particular reason to draw. An outcrop with planar beds of one rock type, with no visible sedimentary structures, variation in bedding thickness, or tectonic structures, does not warrant a field sketch.

Outcrops that are worthy of artistic skill, however, also need to be evaluated first. What is the main reason for drawing the sketch? For example, an outcrop that has interesting sedimentary structures, such as a variety of cross-bedding, would be drawn slightly differently to one that contains several normal faults since different features will need to be emphasized. Examining an outcrop first ensures that all key features can be seen and that the best position to observe and draw the geology is used. For example, can a representative bedding orientation, or in the case of igneous rocks, the contacts and the shapes of the igneous bodies, be seen from the current position? It isn't necessary to figure out every detail before sketching, just enough to know in general what needs to be drawn. Part of the reason for sketching is as an aid for detailed observation, and in fact whilst drawing, additional elements of the geology will be noticed that wouldn't have otherwise been seen.

2.7.2 Rule 2—don't draw too much or too little

Having interpreted the geology, and thus having a reason to draw, it is necessary to decide how much of the outcrop will be drawn. Small outcrops can be drawn whole with some of the surrounding context. Large outcrops are more problematic, in particular cliff faces where there is no obvious edge to outline the sketch. The best choice is to identify the feature that is the subject of the sketch, such as a fault, and decide how much more of the outcrop needs to be drawn to place that feature in context. With a fault, for example, the orientation and nature of beds on either side are important to draw to illustrate the sense of movement and the displacement across the structure. These choices will depend very much on what is being drawn.

2.7.3 Rule 3—don't draw too small

Once the field of view to record has been chosen, the size of the drawing in the notebook must be selected. Those who like drawing often have notebooks full of sketches, with most of their notes done as descriptive labels. A common mistake is to make sketches too small. If it is worth drawing then make it large—half a page at least. The only reason for drawing smaller sketches is if there is one little detail to highlight with a peripheral sketch.

2.8 The stages of drawing

Drawing is easier if split into several stages with different objectives. After applying the three rules, the first stage of drawing is to establish the overall scale and the locations of the important features. These will include the outline of the outcrop or horizon of the landscape, the subject of the sketch, such as a fault or fold, and those features required to provide a minimum context for the subject, such as important bedding planes, as shown in Figure 2.6b. Techniques such as guidelines and the quadrant grid described in Section 2.3 should be used to help ensure the accurate placement of simplified lines during blocking-in since these will be used as a framework for the rest of the sketch.

The second stage is to amend the simplified lines with detail. Protrusions and indents on the initially drawn lines are added. These details will prove useful in placing other objects in the sketch and care should be taken not to exaggerate these features to ensure the geometry remains accurate.

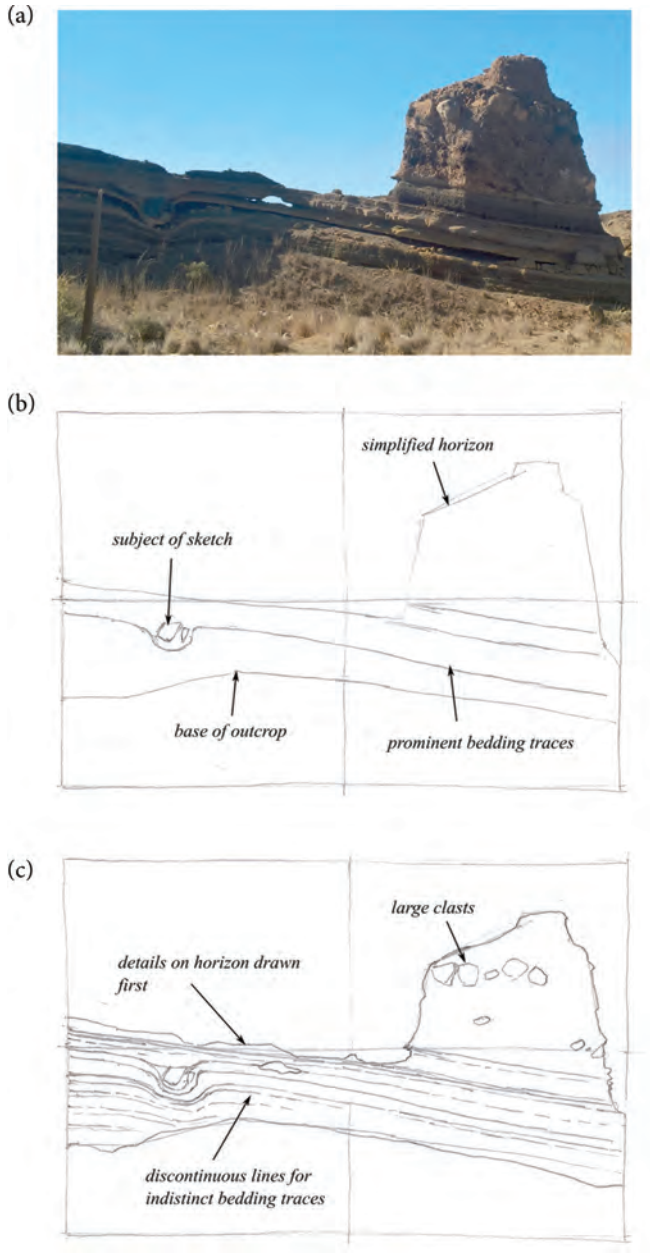

Figure 2.6 Showing the development of a field sketch of a volcanic bomb sag and its context within the Middle Tuff sequence of Santorini.

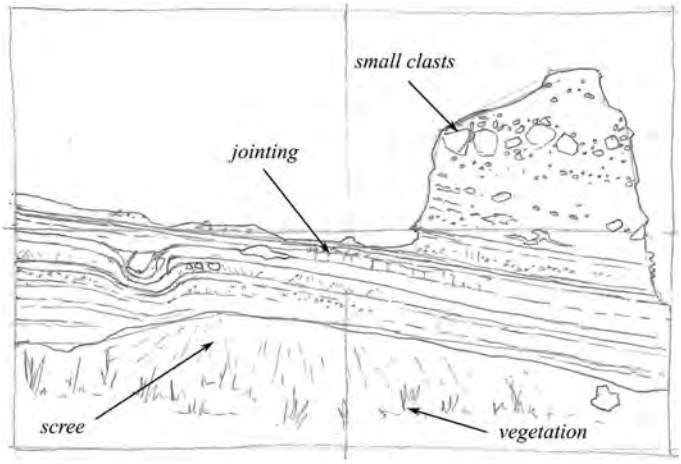

Figure 2.7 Showing the final stage of drawing of the sketch of a volcanic bomb sag.

The next stage in drawing is to add essential geological detail to the diagram. These are elements such as bedding traces, minor faults, and folds etc. that, although not crucial in illustrating the overall geometry, enhance the context for the subject of the sketch. What constitutes essential detail will depend on the objective of the drawing as shown in Figure 2.6c.

Finally, ancillary detail can be drawn that will provide added value to the sketch. These represent features that may prove important in interpretation of aspects of the geology that are separate from the subject. In a sketch intended to show a fault, for example, lithological details, such as clasts and sedimentary structures, could be considered ancillary if they are not required to demonstrate the sense of movement or displacement on a fault (Figure 2.7). When time is available ancillary details should be recorded since often their significance might not be apparent until later.

2.9 Post-drawing tasks

Sketches can, and should be, enhanced after they have been drawn in the field. Raw sketches are still very scientifically valuable, but their value can be increased by a little more work, often at the end of the day.

There are several important guidelines regarding the post-processing of sketches. Firstly, never redraw a sketch. A common mistake is to

move a sketch from one page to another in a notebook in order to fill blank pages and save space. A sketch will never be as accurate when redrawn, and the process wastes time. Similarly, do not add details or change geometry in a sketch after leaving the locality. This usually leads to the introduction of more inaccuracy than it fixes.

2.9.1 Inking-in

An important task to perform on sketches is to replace the pencil lines with ink, commonly known as inking-in. Most university geology courses do not require students to ink-in their notebooks. Inking-in, however, is important for several reasons. Firstly, it preserves the work for life. Pencil lines do rub away and become indistinct, in particular once a notebook inevitably becomes wet and dirty. Adding ink also forces the reviewing of notes after leaving the locality and thus encourages analysis of the geology. This is an important part of planning the next steps during fieldwork. Finally, ink is also necessary before adding colour to sketches.

Inking-in a sketch involves simply drawing over the pencil lines as accurately as possible. It is important not to change the position or shape of lines whilst replacing them. Occasionally some lines can be ignored, particularly if they are clearly mistakes, however, in general every line is replaced by ink. One alteration that can be made at this stage is to emphasis certain lines by increasing line width. With felt-tip indelible pens this can be achieved by adding slightly more pressure when drawing over these pencil lines, or using a pen with a wider tip.

2.9.2 Colouring-in

Adding colour to a field sketch can often greatly improve its clarity and information content. Colour is usually added after inking-in a sketch since it is then possible to remove the original pencil lines with an eraser prior to colouring. In some sketches colour adds little extra value, for example, those in which the subject has little variation in composition and mineralogy. In most sketches, however, colour provides a means of recording information that would either be lost or indistinct. Incidentally, a notebook full of sketches that have been inked-in and coloured looks very aesthetically impressive.

Although colouring-in seems simple, it is easy to ruin a good sketch through poor addition of colour. The choice of colour is important since they should be sufficiently distinct to allow lithologies and units

to be distinguished. Sometimes it is best to use colours that resemble those seen in the field, whilst in other instances schematic colours, for example, those used in a map, are useful. Photographs should be taken of every locality that is sketched and from the drawing position. These provide an approximate record of the colours in the outcrop, and if the data is published, scientific journals prefer annotated photographs rather than sketches.

Using realistic colours provides an opportunity to record additional information. In Figure 3.2c, colour has been used to emphasize clasts and the lenticular areas of dark pumice in the outcrop. Often the colour differences in outcrop are subtle and with the limited palate available in coloured pencils it is usually not possible, or advantageous, to exactly duplicate them. Often it is better to emphasize colour. Sometimes colours can be blended using two different colour pencils by adding one colour over the other, however, if possible, avoid using this method, it can have poor results and turn a sketch into a sickly coloured art joke.

Adding colour is not without technique. Relatively homogeneous coverage of colour is usually preferable for a base layer and is achieved by applying light pressure on the pencil, using the side of the tip by leaning the pencil over. Use relatively long strokes to get good coverage but be careful not to accidently add colour to the wrong place. Holding a pencil in the position shown in Figure 2.8a helps decrease the angle, but also makes it more difficult to be accurate. Most coloured pencils can be partially erased, but it does tend to result in some mess. The objective is to avoid individual pencil streaks being too prominent in the sketch; however, a few streaks are inevitable. Visible streaking usually means an excess of pressure is being used.

Additional methods can be used in colouring-in to improve both the aesthetic and information quality. Texture can be produced using colour pencils that can be used to show the presence of fine-scale features that were not included in the original line-drawing. An example is the presence of clasts that were too small to be drawn with ink. Using a swirling motion with a sharp pencil produces the impression of clasts (Figure 2.8b). Likewise, planar fabrics found in metamorphic and layering in sedimentary rocks can be emphasized with a texture in which linear or curved streaks represent such features (Figure 2.8c). Usually textures are most successfully applied as an additional layer of colour added over a homogeneous base colour. Adding detail colour in several

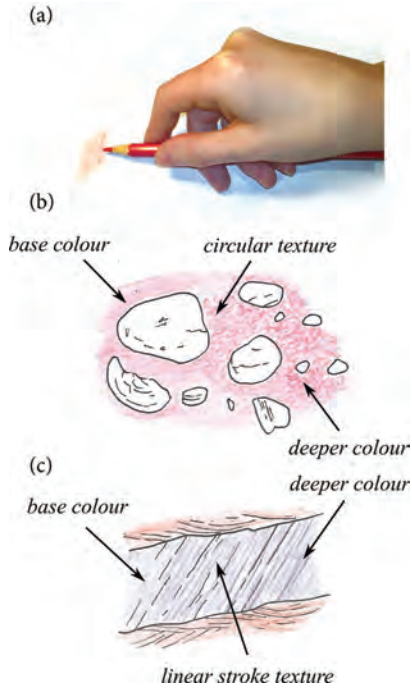

Figure 2.8 Illustrating techniques in colouring-in. To add a base colour the pencil needs to be held at a low angle to the page. Textures can be added after the base colour using a sharpened pencil tip and more pressure.

stages with increasing pressure of the pencil is a useful technique. Adding texture with colour is an advanced technique and is certainly not a requirement for a good field drawing.

Incidentally, please do not let your non-geologist friends read this section of this book. Geologists put up with enough comments about colouring-in without others discovering we have books on the subject.

2.9.3 Shading

Adding shading to a drawing provides the impression of volume and can be very useful in producing realistic sketches of natural objects. Shading does not, however, mean reproducing the shadows observed on an outcrop since these have little scientific significance. Generating shading involves a certain degree of imagination and the ability to mentally filter out some of the shadows that may be present.

Two types of shadow are usually present on objects and form as a result of the two different types of light. Directional light, such as direct sunlight, generates deep directional shadows that have sharp boundaries if cast by a nearby object. These shadows obscure detail and should not be included in a sketch. Diffuse light is produced by the reflection and scattering of light from multiple surfaces or by clouds. The shadows produced by diffuse light are known as ambient occlusion and tend to have gradational boundaries. Ambient occlusion is darkest in areas of a surface that are exposed to the least light sources such as within cracks and indents or on the undersides of ledges and protrusions. Effective shading involves reproducing the effects of ambient occlusion, as shown in Figure 2.9. Two layers of shadowing can often increase realism, but care should be taken not to overwhelm geological features.

Shading in drawings is best achieved using a black or dark grey coloured pencil. A graphite pencil should not be used since the graphite will rub-off and mark the opposite page. Often a grey pencil can be used first for subtle shadows, then a black pencil used to areas of deep shadow. Shading is best added as the last stage in colouring. The gradational nature of ambient shadows can be achieved by varying the pressure used in applying the pencil marks. Ink-pens can also be used to generate shading using closely spaced parallel lines, or by random stipples. These techniques, however, is not recommended since it generates features that are not present and can be confused with geological features such as cleavage and grains.

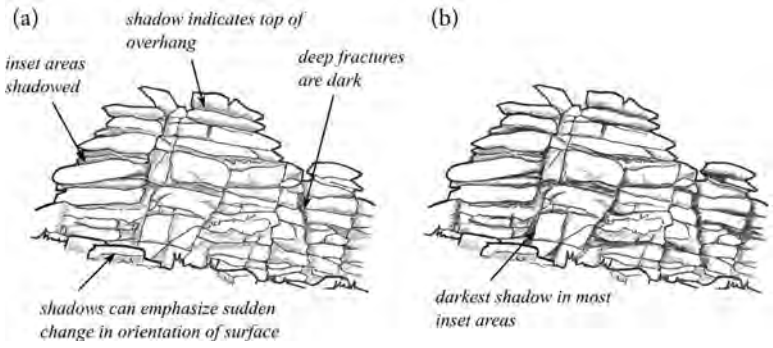
(a)
shadow indicates top of overhang
inset areas shadowed
deep fractures are dark
shadows can emphasize sudden change in orientation of surface
(b)
darkest shadow in most inset areas

Figure 2.9 Illustrating how to add ambient occlusion shadows in a sketch of Rough Tor on Bodmin Moor, Cornwall.

Adding shading to sketches is an advanced technique and requires practice to do well. In general shading is not required to produce a good field sketch but can be used to provide enhanced information on the topography of surfaces.

2.10 Required equipment

A field sketch will be much easier to complete and much more value if done with the right tools. Firstly always use a pencil, never work in pen. A pencil can be erased, because even the most artistic can make a mistake. The worst of all possible choices is to draw (or write) in biro—not only can it not be erased, but the ink will also run and spread in the slightest hint of rain, completely ruining a notebook.

It doesn't really matter what hardness of pencil is used; however, an HB retractable pencil is useful since it is possible to make both faint and bold lines using slight differences in pressure. It is useful to have an eraser at the other end of the pencil. It also never needs sharpening, although it does tend to run out of leads at the worst moment. A lead width of 0.5 mm is usually sufficient since fine lines can be made using the edge of the lead by leaning the pencil over. Hard pencils tend to be difficult to use in the rain on damp notebooks, whilst soft pencils tend to rub off too easily on the opposite page.

Retractable pencils are also useful scales for photographs and measurements since, because they are not sharpened, they stay the same length. They do, however, have an unexpected hazard, some can be magnetic and care should be taken not to hold the pencil next to a compass clinometer whilst taking a reading.

A decent notebook is also essential for a geologist. It should be hard-wearing, have water-resistant paper, and preferably have a cover that makes it easy to find when lost. The notebooks of the Royal School of Mines are, for example, a day-glow yellow that is almost painful to look at, but often can be located on a mountainside with binoculars at a range of several kilometres. It is useful to have plain paper pages; however, faint printed grids can help with the production of logs and cross-sections.

Coloured waterproof (i.e. not water-based) pencils, a ruler, indelible (waterproof) fine-tip ink pens, and a pencil sharpener are also very useful in creating sketches. Pens with nibs of 0.1 mm are usually the best choice. Coloured pencils are particularly useful and the wider the range of colours, the easier it will be to create impressive sketches and maps.

Indelible pens are required for inking-in, an activity that is essential if colour is to be used effectively. A selection of coloured pens is also useful for annotations.

With all this equipment a pencil case, in which it is easy to find implements, is recommended (Figure 2.10). Flip-top pencil cases with holders for each item are perfect for this task. Searching for ten minutes through pockets for a pencil is not the best use of time at an outcrop and an organized pencil case is worth the cost in time saved. Having back-up pencils, pens and erasers is also very useful since geologists tend to leave a trail of these behind them. When you've walked 2 km to get to an outcrop, only to discover you've dropped your pencil somewhere, a back-up can save the day.

Finally, a clear plastic bag, or preferably a weather-writer, is a valuable piece of equipment. Drawing in the rain is inevitable when doing geology—it is almost a rite of passage—and drawing on dry paper is easier than on wet. An umbrella can also serve to provide you with a dry micro-environment in which to work, but is not practical in strong winds.

Figure 2.10 The essential drawing equipment for a geologist.

2.11 When to draw

The natural world has so many complexities that there is virtually always something worth drawing at every locality. Drawing field sketches is, however, a time-consuming activity and, in the field, time is usually limited. The objective of fieldwork is to make excellent, quantitative, and detailed observations. Often field sketches provide the best means of recording this information, particularly when combined with detailed labels. However, drawing should not be allowed to compromise the quality and quantity of field notes. Careful consideration must be given at each locality whether drawing is worthwhile. If the feature in question can adequately be described in one or two sentences, or if the feature is common and is very similar to other examples, then there may be no particular reason to make a field sketch.

Field safety is an important consideration in deciding whether to draw. There are many localities where risk increases with time spent at the location such as under unstable cliffs, on precipitous slopes, on active volcanoes, or where time is an issue because of tides or visibility on the journey back. Always assess the safety of yourself and your companions in the field, whatever activity is being undertaken, and minimize risk wherever possible.

2.12 Sketches and field notebook structure

Geological sketches, schematic diagrams, and maps are just one component of a good field notebook. Quantitative, detailed, and well-structured field notes are also crucial in recording data rigorously. Field sketches should be included together with locality notes in a notebook. Schematic diagrams, maps, and cross-sections frequently combine observations from numerous localities and can be included in separate interpretative sections of a notebook in day or fieldtrip summaries. Good practice in field notes is described in Appendix A.

2.13 Key concepts

In this chapter, several key concepts and methods are introduced:

- Good posture and a comfortable position are required for drawing.
- Use the right equipment.

- Make observations before beginning to draw.
- Decide on how much of the outcrop to draw.
- Don't draw too small.
- Use a quadrant system to help position important objects.
- Start a drawing with simplified lines then add detail.
- Ink- and colour-in drawings where appropriate.

3

Drawing faults

Outcrops with simple geological features that have regular geometries are the easiest to draw, particularly when they are exposed on a relatively flat surface such as a cliff or road cutting. Faults are often in this category since they are broadly planar features, at least on the scale of an exposure, and often outcrop as roughly straight lines intersecting and displacing bedding. Often those who do not like to draw will not sketch these simple exposures; however, these are the type outcrops that should be drawn to improve sketching skills.

In this chapter the use of guidelines and quadrants will be described as a method to ensure that sketches have accurate proportions. Making sure that features in a sketch have the right relative dimensions from the start provides a framework on which to build the rest of the drawing. With the correct proportions even a simple, semi-schematic sketch is valuable and is a useful target for those who find it difficult to draw. This chapter will also introduce how sketches can be built-up in layers with increasing levels of detail to greatly simplify the task of drawing. Finally, a description of the nature of faults will be given since knowing what features are important to draw is a crucial element of sketching geology.

3.1 Drawing a simple fault

A photograph of a simple fault is shown in Figure 3.1 together with a step-by-step example of how to create a sketch of the structure. The fault cuts through pumice lapillistones, ash, and tuff-breccia layers of the Middle Tuff sequence from Santorini in the Aegean. The thought process used in sketching this structure will be described here in detail since it illustrates the degree of observation required in creating good field drawings.

How to start a sketch is usually the first problem encountered. It is tempting to start drawing a single piece of detail, usually the key

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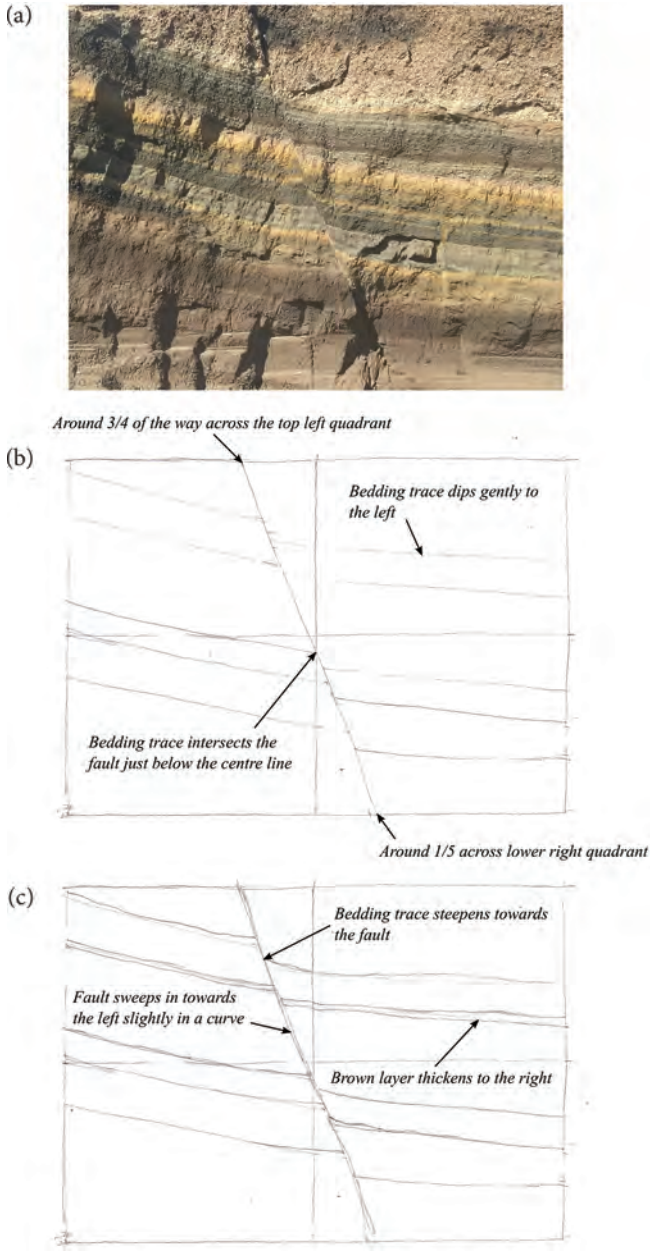
(a)
Around 3/4 of the way across the top left quadrant
(b)
Bedding trace dips gently to the left
Bedding trace intersects the fault just below the centre line
Around 1/5 across lower right quadrant
(c)
Bedding trace steepens towards the fault
Fault sweeps in towards the left slightly in a curve
Brown layer thickens to the right

Figure 3.1 Worked example of a sketch of a simple fault in the Middle Tuff of Santorini.

subject of the sketch such as a fault. This can work, for those who can draw; however, for those who have problems drawing, a more structured approach will help ensure the spatial relationships are correct from the start. Every sketch starts in the same way—with the rules introduced in Chapter 2.

3.1.1 The rules

The first rule in sketching is to look before drawing and evaluate the outcrop. What are the most important geological features to be recorded? What is the purpose of the sketch? In the example in Figure 3.1a the most important feature is the fault; however, it is also crucially important to draw enough of the surrounding sequence to illustrate the displacement of beds. Notice that it is the colour and thickness variations in the beds that allow them to be correlated across the fault.

The second rule is to choose how much of the outcrop to draw. In this case the purpose of the sketch is to record the type of fault and its sense of movement, and any information that can be used to interpret the timing of fault movement. A field of view that encompasses the entire photograph seems reasonable.

The final rule is to choose how large to make the sketch in a notebook. This is a simple sketch with few important features and it can probably be recorded in a half page of a notebook. Usually it is not worth making sketches smaller than a half page, unless they are detailed peripheral sketches. These will be introduced in Chapter 5.

3.1.2 Blocking-in using quadrants

Ensuring a sketch has the correct proportions from the start will make it far easier to create an accurate drawing since the details added later will be guided by the earlier drawn lines. Blocking-in is a drawing technique in which the most important lines are added roughly as a guide for additional detail. In the case of the fault in Figure 3.1 the fault plane and the prominent bedding contacts are the most important lines to be drawn.

A useful technique to ensure the sketch has accurate proportions is to subdivide the chosen field of view into quadrants. This involves being able to imagine a horizontal and vertical line superimposed upon the field of view, which can take some practice. Identifying easy to recognize objects that are halfway across and down the drawing area will help locate other features in the four quadrants.

Quadrants can be drawn directly on the page with an outline of the chosen field of view, as shown in Figure 3.1b. Ensuring the height and width of the outline box are correct is important otherwise the entire sketch will be distorted. A useful way to approximately measure these proportions is to hold a pencil up at arm's length and count the number of pencils across the field of view and the number down. A ruler can be used to add the border and centre lines to the page if necessary.

Positioning the initial lines can now be achieved using estimated coordinates. In Figure 3.1 the fault plane intersects the top of the field of view three-quarters of the way across the top left quadrant, whilst it intersects the bottom of the field of view one-fifth across the bottom right quadrant. These points can be marked on the page, and an approximate straight line can be drawn between them to represent the fault. Similarly, the most prominent bedding traces can be added to sketch taking note of where they intersect the boundary of the sketch and the centre lines. In this sketch the bedding and the fault traces are approximately linear, and straight lines can be used.

3.1.3 Adding detail to key features

After blocking-in, the sketch now has reasonable proportions and the most important features are laid out in broadly the right places; however, the sketch is a gross oversimplification of the geology. The next step is to add accurate details to the essential features.

The fault trace in Figure 3.1 is not entirely straight; it curves to the left in the upper part of the outcrop and slightly to the right in the lower part. The accuracy of the fault trace can now be improved in the sketch using the original straight line as a guide by drawing these gently curved lines. Having the initial approximate line makes it far easier to draw these subtle features without over-exaggeration.

The bedding traces on the cliff face are also not entirely straight. They curve upwards towards the fault on either side by variable amounts. The bedding traces of some beds also gently curve along their lengths. These features can be added using the original straight lines as a guide and using the positions of rises and falls in the bedding trace within each quadrant. The uppermost bedding trace, for example, rises upwards above the original straight line, reaching a maximum deflection about halfway through the upper right quadrant. The bedding trace then moves back towards the original straight guideline toward the end of the quadrant. This shows the thought process and degree of observation used during drawing.

At this stage additional important features can be added, since more will be observed during drawing than at a first glance. A prominent brown ash layer is present at the base of the upper grey lapillistone. It thickens away from the fault to the right. The nearby bedding trace, which has already been drawn, can be used as a guide to draw the upper boundary of the brown ash by paying attention to the thickness of the layer, as shown in Figure 3.1c.

3.1.4 Adding additional relevant detail

The sketch is now accurate and has good proportions. If the purpose of the sketch was to simply record the displacement and geometry of the fault, a drawing with this level of detail would be adequate. There are, however, many other relevant details that could be added giving enhanced value to the sketch. The sequence here is rather complicated with some layers having sharp boundaries, whilst others are gradational. There are also some changes in thickness of beds that are likely to be important in the interpretation of their emplacement as volcanic deposits.

Additional relevant detail can be added using the key lines already drawn as guides. A choice must be made about which boundaries are the most important to draw—a process that involves a geological assessment. Particularly interesting is a lens of black scoria within the lower left quadrant and the slight difference in dip between the upper yellow-ochre ash and the overlying grey pumice lapillistones. Sketching has allowed these subtle features to be noticed.

A particularly important feature is present in the centre of the field of view in the form of a minor fault that splays from the main fault trace. The upper boundary of the prominent grey ash layer is stepped down by this minor fault. There is also a grey fine-grained layer along the fault plane just below the minor fault that is likely to be a fault gouge—broken rock distributed along the fault. These features have been added to Figure 3.2a.

Finally, lithological information can also be recorded in this sketch. Many of the beds contain pumice clasts of varying sizes and some have poorly defined laminations dictated by the size of clasts. The issue with drawing such features is the large number of clasts that are present, which means that not all of them can be drawn. Drawing enough to illustrate the lithological variations is sufficient and is shown in Figure 3.2b. Documenting clasts will be discussed in more detail in Chapter 9 on sedimentary rocks.

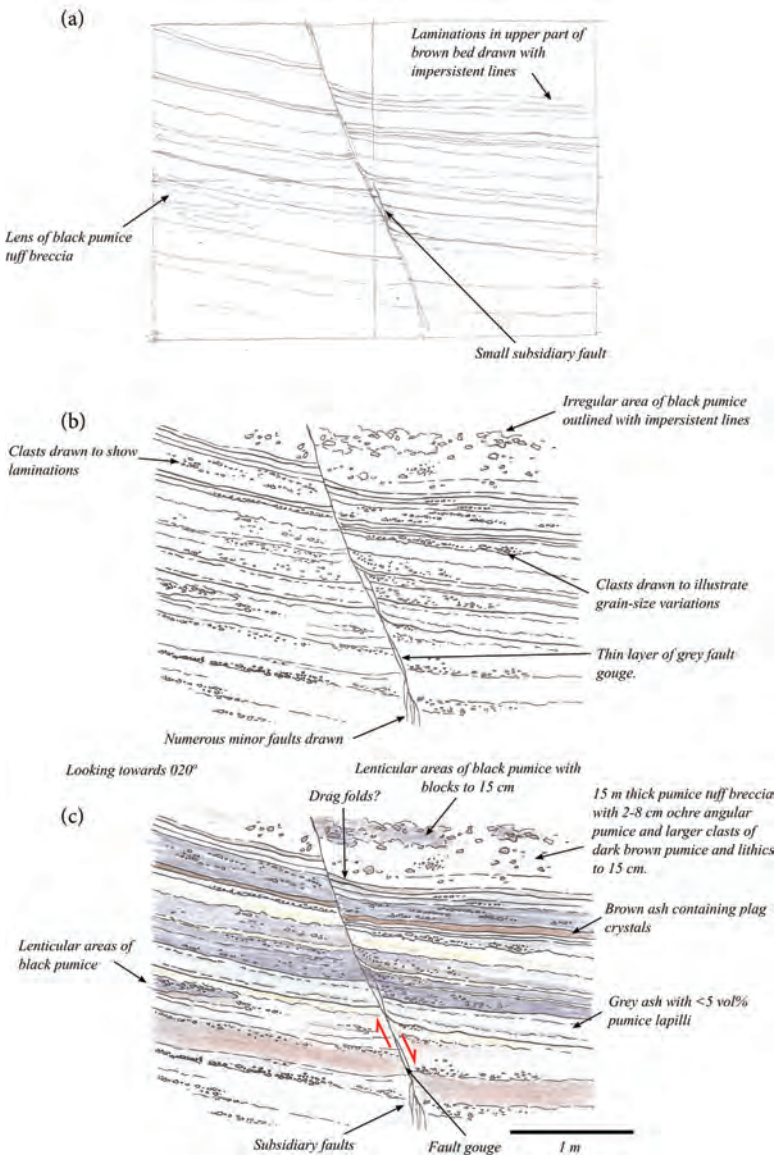
(a)
Laminations in upper part of brown bed drawn with impersistent lines
Lens of black pumice tuff breccia
Small subsidiary fault
(b)
Irregular area of black pumice outlined with impersistent lines
Clasts drawn to show laminations
Clasts drawn to illustrate grain-size variations
Thin layer of grey fault gouge.
Numerous minor faults drawn
Looking towards 020°
(c)
Lenticular areas of black pumice with blocks to 15 cm
Drag folds?
15 m thick pumice tuff breccia with 2-8 cm ochre angular pumice and larger clasts of dark brown pumice and lithics to 15 cm.
Brown ash containing plag crystals
Lenticular areas of black pumice
Grey ash with <5 vol% pumice lapilli
Subsidiary faults
Fault gouge
1 m

Figure 3.2 Final stages of drawing of a simple fault in the Middle Tuff of Santorini.

3.1.5 *Labels and scale*

The last remaining drawing task is crucially important. Geological sketches are scientific diagrams and they require a scale and a looking towards direction. The direction is best given as a compass bearing rather than approximate notations such as 'South' or 'East', which are not accurate.

Although the drawing is finished there is a very important element missing. Sketches must have descriptive labels. Often labels are best added after drawing but whilst still at the locality. Much of the description made at the outcrop can be added to a sketch since it provides spatial context for lithology and structural observations. Knowing exactly where on an outcrop observations were made greatly increases their value.

3.1.6 *Post-drawing tasks*

Sketches should be inked-in after leaving the outcrop, in the evening or whenever time allows. As described in Chapter 2, it is important not to change sketches at this stage. Inking-in merely requires replacing pencil lines with ink to preserve them.

Colouring-in sketches is optional but can be very useful in signifying lithological differences. In the current example there is a significant variation in colour from layer to layer that is likely to relate to a combination of composition and oxidation. Adding colour to sketches means that every layer need not be labelled with lithological notes and greatly improves clarity. In this case it is particularly important since the displacement on the fault is much more apparent if the units are coloured (compare Figures 3.2b and 3.2c). Here the colours used resemble those observed in the field. It is often useful to refer to a photograph when colouring-in since it usually takes place away from the outcrop.

3.1.7 *Adding interpretation*

Interpretation should be added to field sketches using annotations and labels. Some interpretation can be added in the field if it is obvious, but it can also be added later. Interpreting field sketches encourages analysis of their significance and is particularly important in geological mapping where evidence for sedimentary environment and structural evolution accumulates locality by locality and day after day.

In the case of the current sketch the interpretation is relatively simple. The sense of displacement on the fault is clearly normal with the

downthrown hanging wall on the right. Annotations should be added to sketches of faults to show their sense of motion using two opposing half arrows either side of the fault. Coloured ink can be used to highlight the interpretation. When annotating sketches, however, give a moment's thought beforehand—adding arrows the wrong way around in ink would be unfortunate.

Labels can also be interpretative in nature and emphasize features with interesting implications. In the case of Figure 3.2c, beds change orientation close to the fault suggesting these are drag folds caused by motion along the fault. The folds on the footwall of the fault (left side), however, have an opposite sense to the fault displacement and might suggest the fault had periods of reverse movement. Volcanoes often experience repeated subsidence and uplift as a result of the inflation of magma reservoirs.

3.2 The key features of faults

Interpreting sketches of faults involves knowledge of the geometry and terminology of fault structures. The level of interpretation required depends on the geology of the outcrop, the focus of the study, and the level of experience of the observer. A first-year undergraduate, for example, should be capable of interpreting the type of fault exposed in Figure 3.2. There are three types of fault in which the displacement is mainly vertical (dip-slip faults): (1) normal, (2) reverse, and (3) thrust, as shown in Figure 3.3. The fault in this sketch is a normal fault.

Using the correct terminology is important in labels. The different elements of a simple fault are shown in Figure 3.4. Particularly important is the displacement of boundaries by the fault, which in this case is around 20 cm. Identification of the footwall and the hanging wall

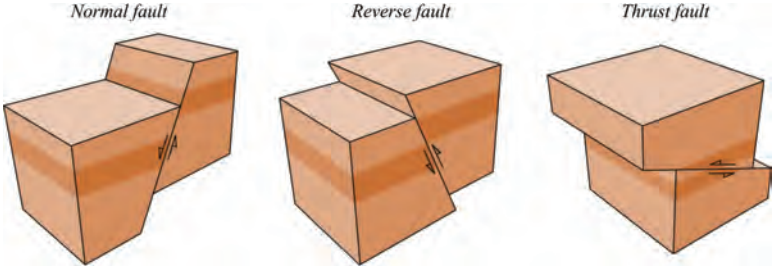

Figure 3.3 Basic types of dip-slip faults.

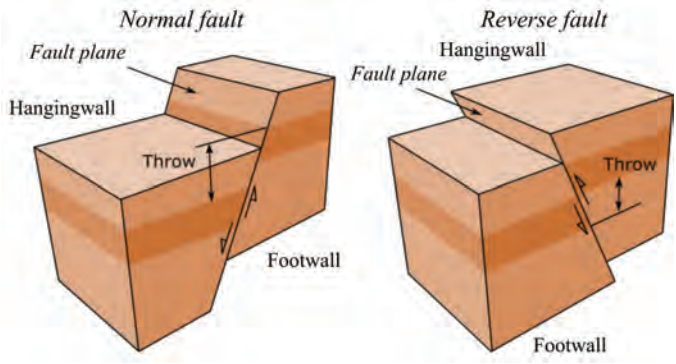

Figure 3.4 The terminology of pure dip-slip faults.

is also crucial in determining the type of fault and thus the stress regime under which it formed. Normal faulting occurs in response to extensional stresses. It isn't necessary to label everything in a sketch and a subjective choice has to be made on what are the most important labels and annotations to add.

The simple fault sketched in Figure 3.2 has an associated minor fault. As is often the case there isn't a single fault plane but a fault zone in which there is more than one slip surface bounding blocks of rock termed horses. There are also subsidiary faults with small displacements splaying from the main master fault. Those subsidiary faults that dip in the same direction as the master fault are termed synthetic faults; those that dip in the opposite direction are antithetic faults. The terminology of these more complex structures is shown in Figure 3.5.

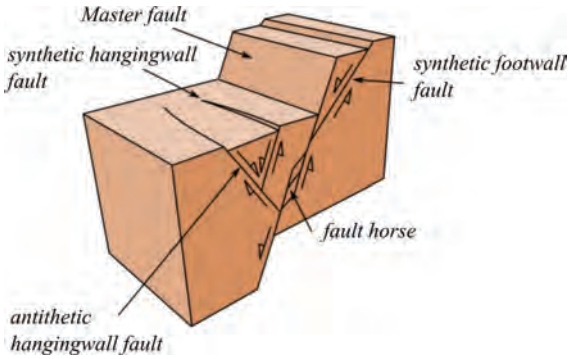

Figure 3.5 The elements of complex fault zones.

3.3 Drawing complex fault zones

A complex fault zone consisting of several parallel faults with synthetic and conjugate fault sets is shown in Figure 3.6. This fault is part of the Moab fault system in Utah, USA and cuts Pennsylvanian limestones. The structure here is much more complex than the simple normal fault used in the first example and presents a challenge in drawing owing to the number of features that must be positioned correctly.

Again, the three rules should be applied before beginning the sketch. The geology needs to be assessed first to identify what are the key features to be drawn—in this case the major faults and the displacement of beds across them. Then the area to be drawn must be chosen—here the entire photograph. Finally, a decision is made on how much space is needed in the notebook for the sketch—for this complex structure an entire page in landscape orientation (sideways) would be appropriate.

Blocking-in the sketch to ensure the right proportions will be crucial for more complex structures such as this fault zone. When there are many inter-related features their positions become vital to the layout of the drawing—if the initial proportions are incorrect, the intersections of faults with each other and bedding will be inaccurate. The best approach to blocking-in a more complex sketch is to use the outline of the exposure as a guideline to help position the features, as well as using quadrants. This exposure is three times higher than its length. The lower boundary of the outcrop is the road and is a line that is inclined gently to the right. The upper boundary is a smooth asymmetric curve that reaches a maximum height just under halfway across the upper right quadrant.

The most important key features are the faults, since they control the position of the bedding planes separating the different units. The faults, therefore, must be drawn first. Adding the faults can be achieved relative to the outline of the exposure and the quadrant grid. One fault, for example, runs up from a point on the road, nearly at the centre line, and reaches the top of the exposure at around two-thirds of the way across the upper left quadrant. A smaller subsidiary fault splays from this master fault at the road line and is initially vertical for a short distance and then runs parallel to the master fault.

As the key features are added to the sketch they become guidelines to help position the next feature to be added. The antithetic subsidiary

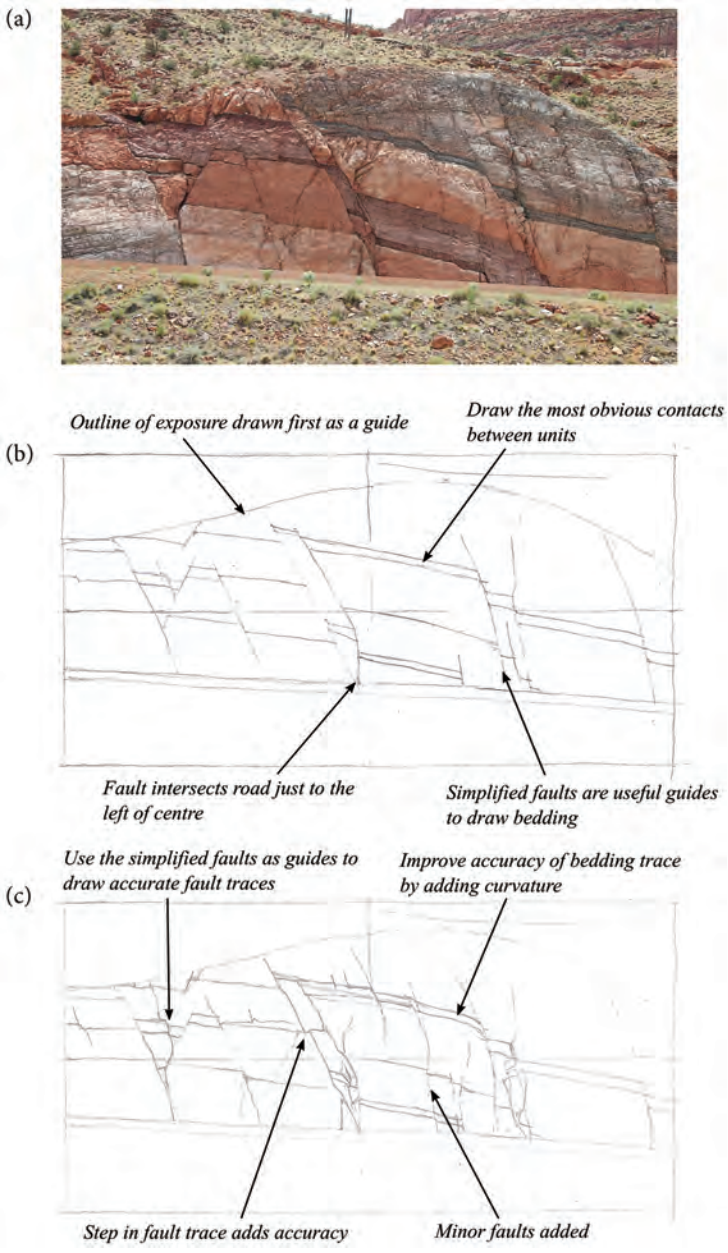
(a)
(b)
Outline of exposure drawn first as a guide
Draw the most obvious contacts between units
Fault intersects road just to the left of centre
Simplified faults are useful guides to draw bedding
(c)
Use the simplified faults as guides to draw accurate fault traces
Improve accuracy of bedding trace by adding curvature
Step in fault trace adds accuracy
Minor faults added

Figure 3.6 Initial stages of sketching of the Moab fault zone, Utah (photo credit: James St John).

fault in the left upper quadrant, for example, splays off its master fault at around one-third the way up the fault from the road, it reaches the top of the exposure a small distance to the left of the first fault added to the sketch. Thinking about the spatial relationships between the structures as they are drawn makes it considerably easier to ensure they fit together accurately.

Once the faults have been added to this sketch, then the important bedding contacts between units can be drawn. The thickness of the beds relative to each other is important and allows one bedding trace to be used as a guide for the next. The displacement of the units across the fault surfaces is also crucial.

When blocking-in a sketch with many key features, mistakes are inevitable. Often it will be discovered that a fault has been added in the wrong place, making it difficult to insert other features such as contacts between units. It is worth the extra time to erase the erroneous fault and amend its position. The completed simplified sketch is shown in Figure 3.6b and would make a reasonable, if schematic, field sketch.

Detail can now be added to the key features. The faults are not as straight as they have been drawn and have several important features that should be recorded, such as a minor step in one of the master faults, and a curvature on some of the subsidiary faults at their intersections. The original straight lines used for the faults and the intersections with the units make useful guides by which such detail features can be positioned. During this process, which forces close observation, many less important features will be noticed, such as minor faults with small throws. These can also be added during this stage, as shown in Figure 3.6c.

The final stages of sketching the Moab fault zone are shown in Figure 3.7. Additional details that are geological relevant should be added. In this case laminations within the limestones provide some sedimentological information, in particular the large scale cross-bedding in the uppermost limestone bed and interlaminations of mudstone in the thin, grey limestone. Discontinuous lines can be used to indicate the less prominent nature of these features.

Labels and annotations complete the drawing, together with a scale and looking towards direction. The sense of movement on faults is particularly important to interpret. Colour is also very useful in this sketch since it emphasizes the subtle differences between the different limestone beds and the displacements across the faults.

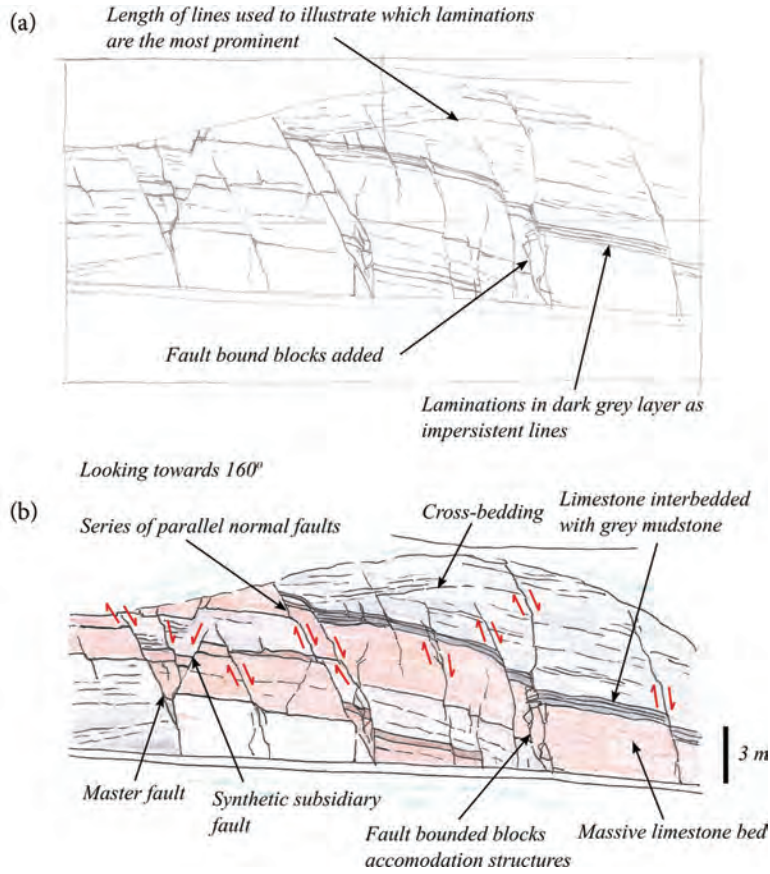

Figure 3.7 The final stages of sketching the Moab fault zone, Utah.

3.4 Common mistakes

3.4.1 Vertical exaggeration

When exposures are large and drawn from nearby they can appear higher than when viewed from a distance. This perspective effect often leads to vertical exaggeration that distorts the spatial relationships. Comparing Figures 3.8 and 3.7, a vertical exaggeration of around 1.5× can be seen in this example and leads to overly vertical faults and smaller intersection angles. Being aware of this perspective effect and choosing a suitable position to sit and draw an exposure helps prevent

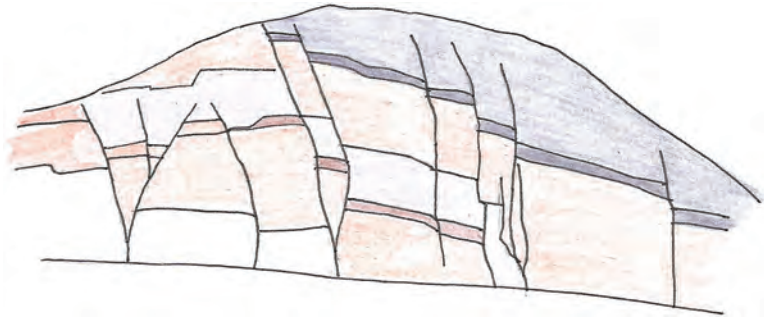

Figure 3.8 Vertical exaggeration of a field sketch.

vertical exaggeration. A poor drawing position, however, is always better than a dangerous drawing position, especially in the vicinity of roads.

3.4.2 Oversimplification

Although field sketching necessarily involves simplifying the geology and a focus on the most important features, oversimplification leads to schematic sketches with inadequate detail and accuracy. Somewhat schematic sketches, such as Figure 3.9, do, however, have value and can be a real achievement for those who finding drawing difficult. Oversimplification often arises because of a lack of time. Wise selection of what to draw can help, since fewer detailed sketches are better than many schematic drawings. Practice also will improve drawing confidence and speed, and thus give more time to add important detail.

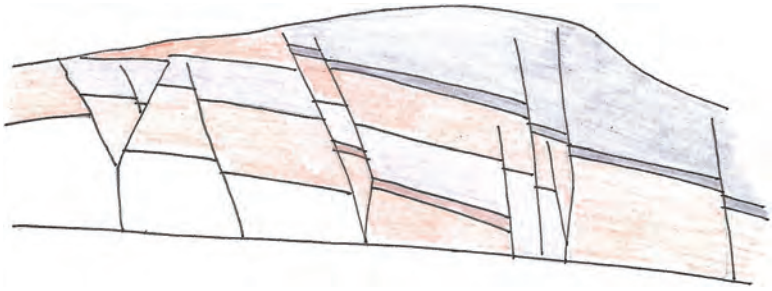

Figure 3.9 An oversimplified field sketch.

3.5 Key concepts

In this chapter several key concepts and methods were introduced:

- The dimensions of a sketch are crucial to establish correctly from the start.
- Quadrants can be used to help position objects in a sketch.
- Block-in a sketch with simple lines showing the most important features.
- The first features to be drawn are those that control the positions of other features.
- Add accuracy to the key features before adding additional relevant detail. Build up the sketch by adding increasing levels of detail.

4

Drawing folds

Exposures with folds provide an additional drawing challenge since bedding changes in orientation. Folds are common and vary greatly in scale from minor parasitic folds, a few centimetres across, to those with wavelengths of many kilometres, which can rarely been seen in their entirety in the field. Folding, like faulting, records the deformation of rock sequences and thus relates to periods of tectonic upheaval that are often related to major orogenies. Observations of the orientations and geometries of folds allows the individual deformation phases that make mountain building events to be recorded and related to plate tectonics.

In this chapter tactics useful in drawing folds will be described that ensure the symmetry of the structure is recorded accurately. These techniques involve drawing the trace of the fold axial plane on the outcrop—a feature that cannot usually be seen and thus must be imagined. Drawing folds is thus more difficult than drawing faults in which the fault trace is an observed feature. Unlike a picture completely drawn from the imagination, however, the fold axial trace is interpolated from the observable features in the outcrop and its position is usually well constrained.

4.1 The geometries of folds

The geometries of folds vary considerably and are important to record within drawings of outcrops. Folds consist of a hinge region, where most of the curvature of the beds occurs, with limbs either side of the hinge, where bedding is more planar. The angle between the limbs, the inter-limb angle, defines the tightness of folds. Gentle folds have interlimb angles greater than 120°, open folds have interlimb angles of 80–120°, close folds 30–80°, and tight folds <30°. The term isoclinal is used for those folds in which limbs are nearly parallel, having inter-limb angles of <10°. Folds also vary in shape and include chevron folds that have abrupt hinges and straight limbs, box folds consisting of two

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intersecting kink bands (conjugate sets) and rounded folds in which the limbs exhibit continuous curvature. Folds are described as synforms when they have a downwards curvature and antiforms when they have an upwards curvature. When beds are the right-way-up these folds are termed synclines and anticlines respectively. Synforms and antiforms occur adjacent to each other and can be symmetrical in shape, or asymmetrical with a long limb and a short limb, as shown in Figure 4.1.

The key symmetry element of a fold is its axial plane. The fold axial plane is the surface that divides the fold shape symmetrically and lies mid-way between the limbs, as shown in Figure 4.1. The fold axial plane has a special significance since it is oriented perpendicular to the direction of maximum compressive stress. Consequently, folds formed in the same deformation event have broadly parallel axial planes and are the same generation of fold. The ridge formed by the hinge is called the fold axis or hinge line and it lies within the fold axial plane. Often the hinge line is inclined, and the fold is said to be plunging. This lineation forms a line that can be measured as a plunge and plunge direction.

Drawing folds involves faithfully recording their geometries in terms of the tightness, shape, and the symmetry elements of the fold. All of these properties are related to the position of the fold axial plane, which is thus the most important feature to observe. Often folds are exposed in three dimensions rather than in section on a flat surface—such structures pose additional difficulties that are described in Chapter 6 on drawing in three dimensions. More complex superimposed fold geometries caused by several phases of deformation are described in Chapter 5.

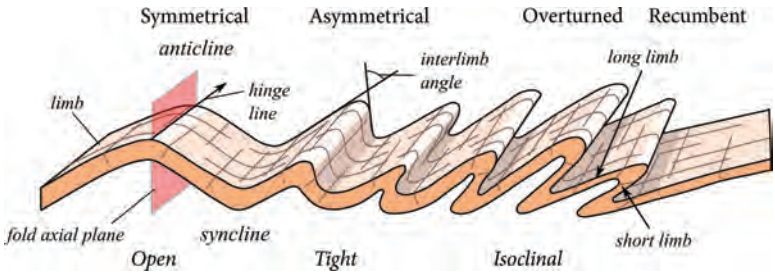

Figure 4.1 Different types of fold by shape and tightness.

4.2 Drawing an open fold

The key to sketching folds is to draw the trace of the fold axial plane on the outcrop to guide the geometry. This involves drawing a line that cannot be seen and thus its position must be imagined. In the example shown in Figure 4.2, a simple fold located in Pen-y-holt in Wales will be drawn and is an open asymmetric fold in well-bedded limestones.

The first step in drawing the fold is to apply the three rules. First look and broadly interpret the structure. Here two folds are exposed: an anticline near the centre of the image and a syncline further to the left. The limbs either side of the fold axes are asymmetric with a long limb on the right of the anticline and a short limb on the left. The trace of the fold axial planes lies along the line of symmetry between the two limbs, and is also the position of maximum curvature of the beds at the hinge. The axial trace can be followed with the eye where it intersects the bedding traces on the cliff.

The second rule is to decide how much to draw. In this case the entire photograph gives a convenient size. Finally, the size of the sketch in the notebook is chosen. This exposure could be drawn in a half page of a standard size notebook.

Drawing starts by evaluating the height and width of the chosen field of view. In this case, the drawing will 1.5 times as wide as it is high. A quadrant grid can also be drawn on the page to help position the initial lines. Adding the outline of the cliff is a good starting point since these lines will define the area in which most of the subsequent detail will be added. The outline is formed by a near horizontal line marking the top of the cliff and a horizontal line with an inclined step at the base of the cliff. A platform, formed of beds, also extends from the cliff and its outline can also be drawn.

The axial traces are the next feature to be added to the sketch. The axial trace of the syncline rises up from the point where the base of the cliff meets the protruding beds and forms a line that runs up the cliff; dipping steeply towards the right. The trace of the anticline is nearly parallel to that of the syncline but has a slightly steeper dip. Once added the two axial traces can be used to guide the geometry of the beds, since these will be symmetric either side of the traces.

There are many beds that could be added to the sketch and it is difficult to draw them all. Choosing to add only the most prominent

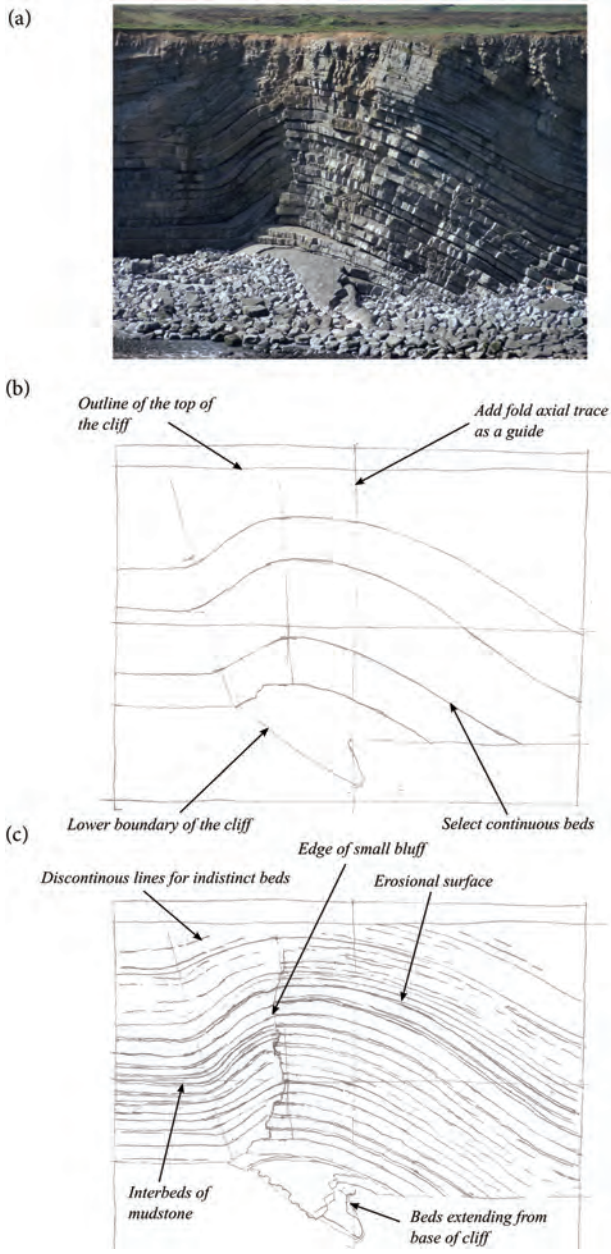

Figure 4.2 The initial stages of a sketch of folds at Pen-y-holt in Wales (photo credit: Ian Paterson).

bedding traces at first makes it easier to establish the geometry of the fold on the page, as shown in Figure 4.2b. These initial beds can be used as guides to draw the surrounding layers. The beds can be added one by one by paying attention to their relative widths.

In drawing the bedding numerous details will be noticed. Firstly, there are thin shale laminations between the thicker limestone beds. These can be drawn by close, nearly parallel lines. By drawing along beds and following the thickness of the shale beds it will be noticed that some thicken at the fold hinge and others are discontinuous and disappear along their length. A particularly interesting shale bed seems to be truncated by an overlying limestone layer suggesting an erosional surface is present, as labelled in Figure 4.2c.

Whilst drawing beds a discontinuity is noticed over which the bedding trace changes position. Unlike a fault the discontinuity is irregular and stepped. This is a small bluff in the cliff and the discontinuity is formed by perspective since the cliff is slightly closer to us on the right than the left. Since this feature affects how the beds, and thus the folds appear, it is important to include in the sketch.

A vertical change in the beds was also noticed whilst drawing. From the base to just over halfway up the cliff the sequence consists of limestone beds of similar, but not identical thickness, with thin shales beds in-between. In the upper part of the cliff the shale beds disappear and bedding traces between layers of limestone become indistinct. The limestone beds also appear to be thinner. These can be added as discontinuous lines indicating a degree of uncertainty in their lateral extension, as shown in Figure 4.3a.

All the important geological detail has now been included in the drawing; however, there are some minor features that, although ancillary, have some relevance. Joints are present in the limestone and are largely oriented perpendicular to the bedding plane. Some of these joints can be added to the sketch, however, it is important not to obscure the important features by adding too many.

The final stage of the drawing is to add a scale, looking direction, labels, and annotations. Some observations on the sedimentology have been added and annotations to mark the fold axial traces. More detailed labels, such as lithology notes including the presence of fossils and sedimentary structures, could be added if the exposure was observed at close range.

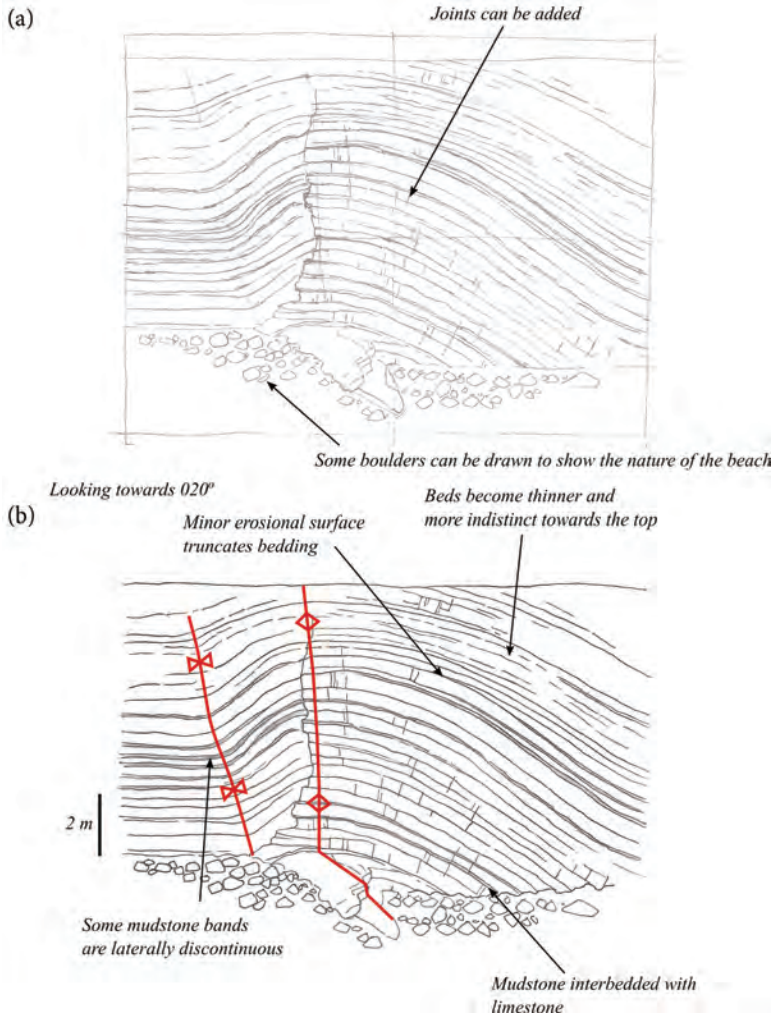
(a)
Joints can be added
Some boulders can be drawn to show the nature of the beach
(b)
Looking towards 020°
Minor erosional surface truncates bedding
Beds become thinner and more indistinct towards the top
2 m
Some mudstone bands are laterally discontinuous
Mudstone interbedded with limestone

Figure 4.3 The final stages of a sketch of folds at Pen-y-holt.

4.3 Sketching a box fold

Box folds consist of two intersecting (conjugate) kink bands that cross to make a rectangular-like shape. Often, they have structures in their centres to accommodate the strain imposed by their otherwise regular shapes. Kink bands form in layered sequences where bedding or

laminations are all of similar width and have very different strengths. Their sizes depend on the width and mechanical properties of the layers. Often kink bands form in the final phase of orogenic deformation when metamorphic rocks become strongly layered by foliations. Box folds have a principle stress axis that lies half way between the obtuse intersections between kink bands.

Box folds and kink bands are more difficult to draw than other simple folds since they can be considered to have four separate fold axes, each bounding kink bands. Their seemingly regular shapes also tend to lead to oversimplification in sketches. An example of a box fold from Cull Bay in the Grampian Highlands of Scotland is shown in Figure 4.4 and illustrates the difficulty posed for sketching. In particular the near constant width of the beds in the fold means there are few characteristic horizons that can be traced around the fold to reveal its geometry.

During the observation stage of the structure the important kink bands need to be identified. The fold is generated by two kink bands that intersect in the centre of the image. The two bands are different widths and varying along their length. The angle between them is approximately 60° indicating a view almost along the fold axis. A prominent bed can be seen just above the centre of the fold and is a layer covered with lichen. Several other lighter siltstone laminations can also be seen.

After the area to be drawn has been chosen, in this case the entire photograph, and the size established in the notebook, a rectangular grid can be used to help block-in and position features. The first features to be added are the kink bands. Their positions at the boundary of the field of view can be used to ensure their relative angles are correct. The variation in thickness along their length can also be included at this stage since this will determine the deflection of the laminations. For now, the most prominent beds and fractures can be added since these provide useful features to position later added bedding traces, as shown in Figure 4.4b.

The indistinct nature of the laminations in this exposure makes it difficult to follow many of the bedding traces laterally. These can be added as short discontinuous lines using the previously drawn layers and the kink band margins as guides. The layering mainly changes orientation at the margins of the kink bands, however, there are some smaller scale gentle folds within the bands. Particularly important is

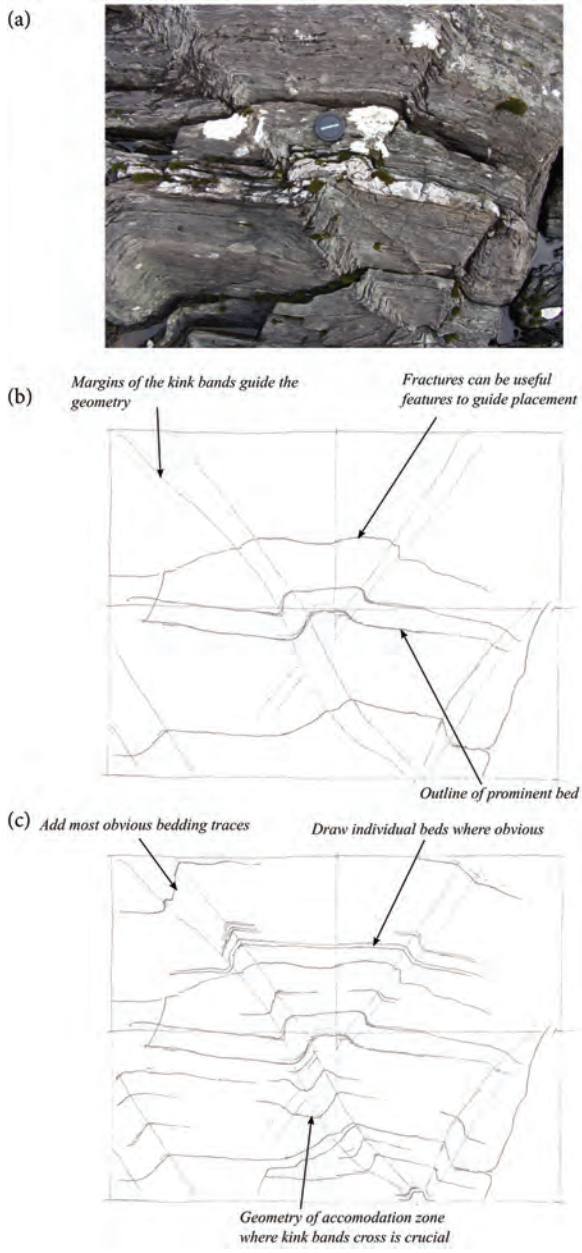
(a)
(b)
Margins of the kink bands guide the geometry
Fractures can be useful features to guide placement
Outline of prominent bed
(c)
Add most obvious bedding traces
Draw individual beds where obvious
Geometry of accomodation zone where kink bands cross is crucial

Figure 4.4 The initial stages of a sketch of a box fold from Cull Bay in Scotland.

the geometry of the folding in the area where the two kink bands cross to form an accommodation structure. Adding the most prominent laminations allows the level of detail of the sketch to be improved whilst maintaining accuracy, as shown in Figure 4.4c.

The final stage of drawing is to add less important horizons to the sketch to improve detail. If little time were available, this stage could be omitted and still result in a good field sketch. The most important areas to add ancillary detail are in the kink bands and in the region where they intersect.

Once drawing is complete some interpretation should be added. For kink bands, fold axial traces could be added in coloured ink and some details on lithology and structure labelled. Scale and orientation is always added to every sketch. Since this drawing is in plan view, a north arrow is the best way to record orientation, as shown in Figure 4.5.

4.4 Common mistakes

4.4.1 Irrelevant detail

Sometimes less important geological features, such as jointing, can be particularly prominent. A common mistake in field sketches is to emphasize less important features such as jointing because they are the most obvious features seen in the outcrop. An example of such a sketch is shown in Figure 4.6. The objective of field sketches, however, is to emphasize the most important geological features and minimize the least relevant. What constitutes an important feature depends on the reason for the sketch. Unless jointing is the primary feature of interest it is usually best to include few joint planes.

4.4.2 Oversimplified strata

When drawing folds the objective is often to record the geometry and orientation of the structure, whilst the nature of sequence is less important and often more time consuming to record. Some attempt, however, should be made to indicate differences in bedding width, and in particular subtle cross-cutting relationships that can affect the appearance of fold limbs. In the example shown in Figure 4.7, the fold geometry has been drawn with reasonable accuracy whilst the beds are schematic and almost equal in width. A little more time spent drawing the sequence more accurately would have added considerable value.

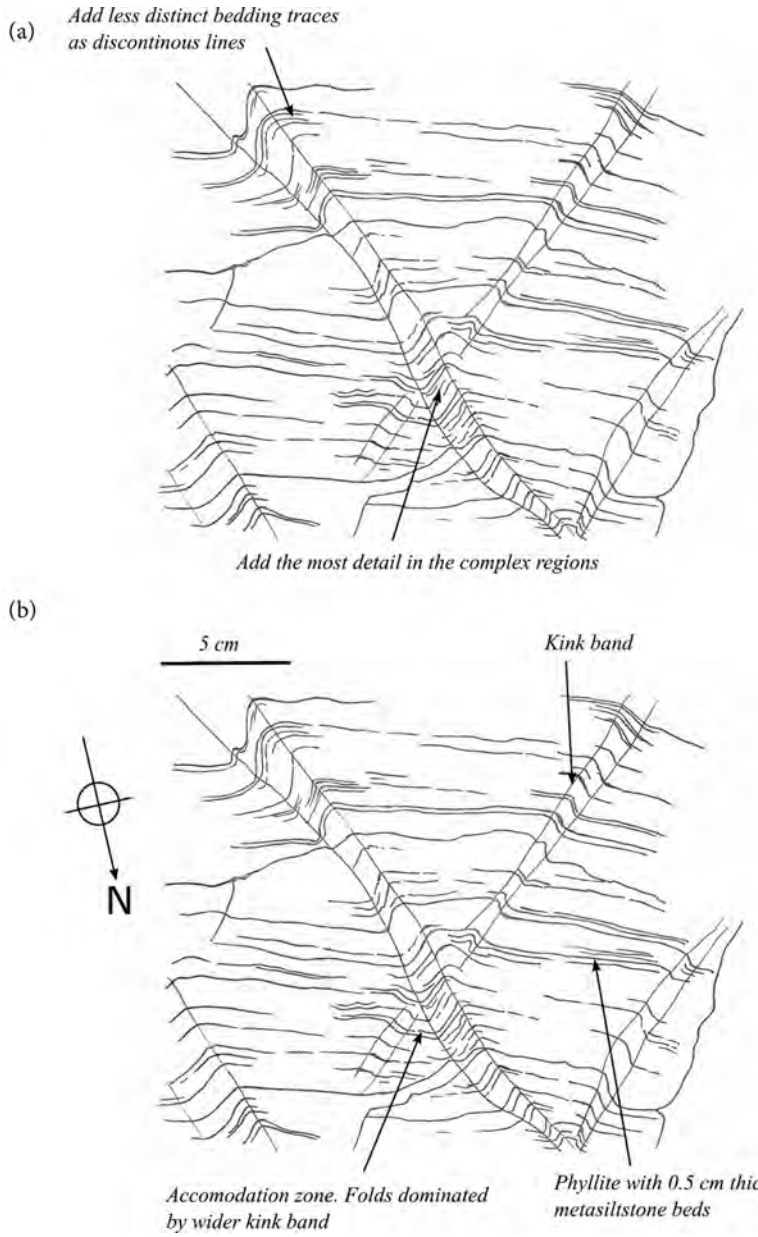
(a)
Add less distinct bedding traces as discontinous lines
Add the most detail in the complex regions
(b)
5 cm
Kink band
N
Accomodation zone. Folds dominated by wider kink band
Phyllite with 0.5 cm thick metasiltstone beds

Figure 4.5 The final stages of a drawing of a kink-band from Cull Bay.

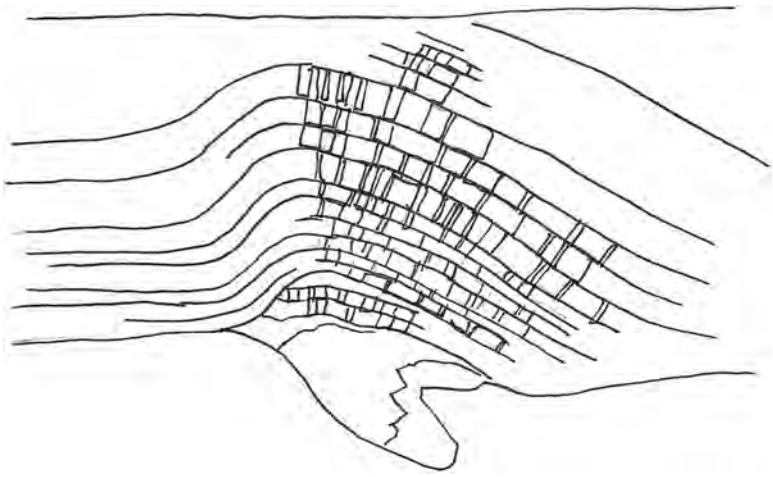

Figure 4.6 A sketch that has put too much emphasis on jointing.

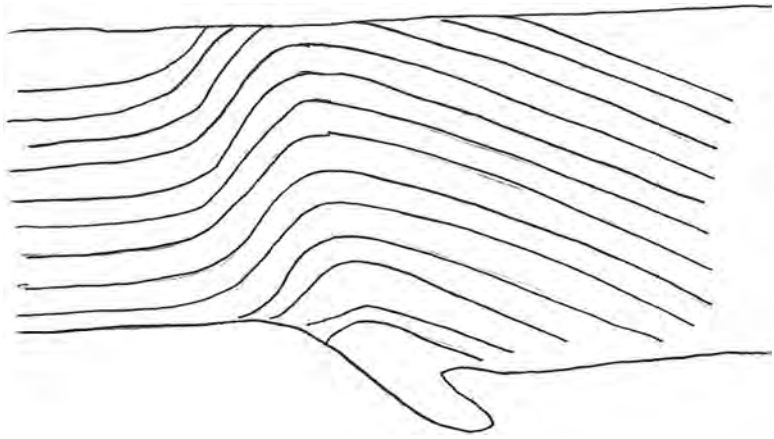

Figure 4.7 A sketch with schematic bedding.

4.5 Key concepts

In this chapter several key concepts and methods were introduced:

- Careful observation is needed in drawing fold structures prior to drawing to identify the trace of the fold axial planes on the outcrop.

- Fold axial traces should be added to the sketch during initial blocking-in to guide the geometry of the structure and position of beds.
- Bed width and cross-cutting relationships are important to record to produce an accurate sketch of folds.
- Less important features can and should be added to sketches, but care should be taken not to obscure the key geological features.

5

Drawing complex structures and metamorphic rocks

Metamorphic rocks formed by regional metamorphism are often difficult to draw owing to the complexity of the structures they contain and the presence of fabrics, which introduce important small-scale details. Often in metamorphic terrains intense folding has occurred with several superimposed sets of folds resulting in interference patterns with geometries that are difficult to draw accurately. Disruption of bedding owing to boudinage furthermore makes it challenging to extrapolate fold axial traces over large distances. The saturation of features and detail in metamorphic rocks makes them challenging subjects for a field sketch.

In this chapter, an approach to drawing outcrops of metamorphic rocks will be described that focuses on assessing what are the most important features to draw. This approach involves being able to identify textural and structural features as well as a degree of understanding of how they formed. Consequently, this chapter begins with a brief description of the most important elements of metamorphic petrology and polyphase structures to better understand the example sketches presented later.

5.1 About metamorphic rocks and their structures

Metamorphic rocks form by recrystallization of pre-existing rocks under the influence of enhanced pressure and temperature. Metamorphism can occur because of an increase in temperature alone, for example, owing to proximity to a body of magma, resulting in thermal or contact metamorphism. It can also occur as a result of deformation at broadly constant temperature, often related to faulting, producing dynamic metamorphic rocks. Much more abundant, however, are metamorphic

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rocks produced by changes in both temperature and pressure, which results in both recrystallization and deformation. These regional metamorphic rocks dominate orogenic belts worldwide and are the principle subject of this chapter.

5.1.1 Fabrics and foliations

Recrystallization and alignment of minerals produce fabrics and foliations within metamorphic rocks that often dominate their appearance at the scales of hand specimens and outcrops. These features have specific spatial relationships to folds that are important to understand when drawing exposures of metamorphic rocks.

Cleavage is a planar fabric that forms by the alignment of platy minerals such as clays and micas. The alignment of platy minerals occurs by their rotation or recrystallization during compression so they become perpendicular to the direction of maximum stress (the principle stress direction). The axial plane of folds and the planes of cleavage formed by the same compression are parallel, since the principle stress direction also controls the orientation of folds. Cleavage formed parallel to the fold axial plane is known as axial planar cleavage and is illustrated in Figure 5.1.

Cleavage is best developed in rocks whose protoliths contained abundant clay minerals, such as mudstones, but can be developed within

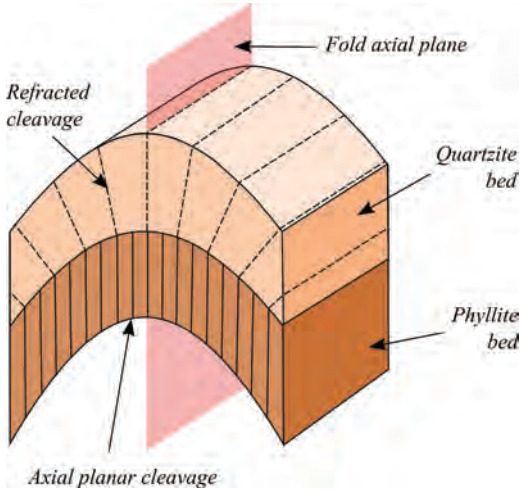

Figure 5.1 Showing the relationship between axial planar cleavage and the axial plane of a fold.

muddy sandstones or limestones. Mud rocks, also termed pelites, experience changes in their mineralogy during metamorphism that lead to different types of cleavage.

At low metamorphic grade pelitic rocks form slates as their original clay minerals are transformed into the clay illite. Slates are very fine-grained and the cleavage formed by the alignment of their illite crystals is known as slaty cleavage. It is a pervasive cleavage that penetrates the rock with closely spaced planes. With metamorphism to higher temperatures and pressures (to greenschist facies) chlorite and then muscovite are formed and produce metamorphic rocks known as phyllites. Increase in the size of platy crystals results in reflective cleavage planes that make phyllites easy to distinguish from slates—although usually individual crystals cannot be seen with the naked eye.

Phyllites have often experienced several phases of deformation, each of which produces folds in different orientations. The pervasive cleavage in phyllites is formed by the alignment of mica minerals parallel to the axial planes of the first generation of folds. Subsequent deformation folds the pervasive (slaty) cleavage to generate small crenulations. The axial planes of the crenulations are parallel to the axial planes of larger folds formed at the same time. The alignment of the crenulations forms a new spaced cleavage known as a crenulation cleavage. This cleavage is non-pervasive and consists of fractures separated by thin slices of rock termed microlithons. The formation of crenulation cleavage and its geometric relationship to folds is shown in Figure 5.2.

With increasing metamorphism to the upper greenschist facies and lower amphibolite facies muscovite increases in crystal size and biotite appears. Once mica minerals such as muscovite and biotite become large enough to be seen with the naked eye, metamorphosed pelitic rocks are termed schists. Their cleavages, however, are very similar to those of phyllites, having reflective cleavage planes. When schists are subjected to later deformation, the pervasive schistose fabric folds to form crenulations and crenulation cleavage. A range of different metamorphic minerals also appear within schists with garnet, kyanite, sillimanite, and staurolite being particularly important. Phyllites and schists also commonly contain abundant quartz veins resulting from silica-rich fluids released by metamorphic reactions.

At higher metamorphic grades cleavage begins to recrystallize to form a gneissose foliation through the separation of felsic minerals,

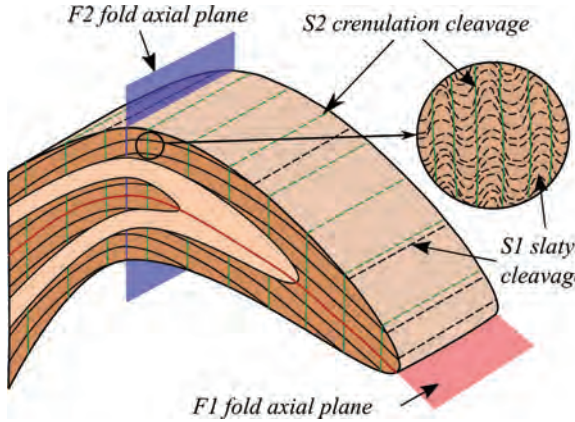

Figure 5.2 The spatial relationship between folds and crenulation and slaty cleavage. The inset shows a magnified view in which the alignment of crenulations in the slaty cleavage can be seen.

such as quartz and feldspar, from mafic minerals, such as hornblende and biotite. Gneissose foliations thus consist of alternating mafic and felsic-rich bands and define the rock type gneiss. Foliations in these rocks also form perpendicular to the principle stress direction and frequently destroy pre-existing cleavages. They tend to develop initially parallel to a crenulation cleavage.

At the highest metamorphic grades partial melting occurs with the generation of silica-rich melts known as leucosomes and mafic-rich unmelted materials known as resistites. Metamorphic rocks that have experienced partial melting are known as migmatites and are typified by diffuse felsic bands that cross-cut and intrude existing banding. An example of migmatite is shown in Section 8.1.2 on igneous rocks.

5.1.2 Folds in metamorphic rocks

Phyllites, schists, and gneisses have usually experienced several phases of deformation, often with increasing numbers of deformation events recorded with increasing metamorphic grade. Such polyphase deformation results in superimposed folds that produce complex folding patterns through interference. It is, however, possible to identify the geometrical relationships and principle stress directions of different folding events through the patterns formed by folds and their spatial relationships to cleavages and foliations.

Fold interference occurs when two or more generations of fold are superimposed. Usually folds become tighter, with smaller interlimb angles occurring with increasing numbers of deformation events. The first generation of folds, therefore, tend to be tight or isoclinal, whilst the last generation of folds tend to be open or gentle. The classification of fold shapes and the terms used to describe them were described in Section 4.1.

A simple, but fundamental, concept in understanding superimposed folds is that the axial planes of earlier generations of fold become deformed around those of later folds. The axial planes of early folds thus become curved surfaces rather than flat planes, and their axial traces on a surface, become curves rather than straight lines. Only the axial surfaces of the last generation of folds are usually planar and parallel. This simple relationship is illustrated in Figure 5.3. It is, therefore, easy to identify the youngest folds in an outcrop since not only do they tend to be gentle, but their axial planes are broadly parallel. The patterns created in beds from superimposed folds are also characteristic and vary depending on the geometric relationship between the different generations of folding.

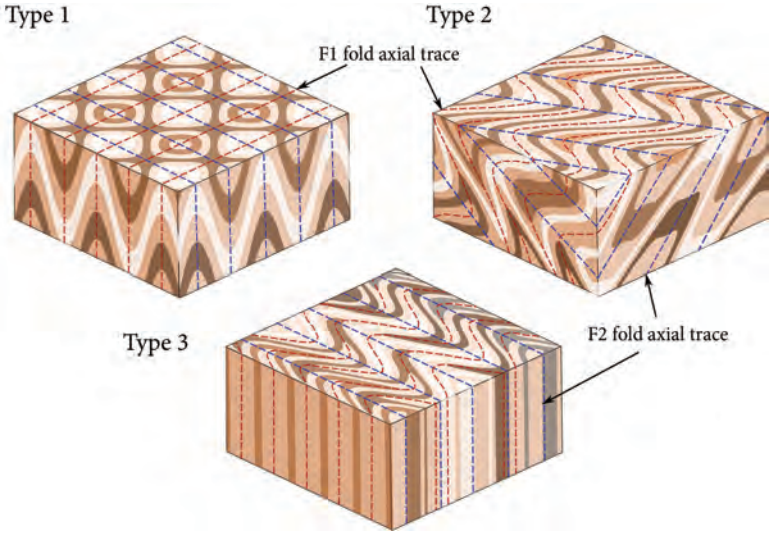

Figure 5.3 Fold interference patterns showing the axial traces of the first F1 folds (red) and the later F2 folds (blue).

Cleavages form roughly parallel to the axial planes of the folds generated during the same deformation event. Often in metamorphic rocks there are several cleavages present and each formed in a different deformation phase and is parallel to the axial plane of a different set of folds. Slaty cleavage, formed by the alignment of the platy minerals, is the earliest of the cleavage sets and is usually parallel to the first formed folds (Figure 5.2). These folds also tend to be the tightest. Later cleavages are crenulation cleavages and are parallel to the axial planes of the later folds. The presence of crenulation cleavage, therefore, always indicates there is more than one deformation event. There can also be more than one set of crenulation cleavage, each having a different orientation. These multiple crenulations are best seen on the reflective slaty cleavage surface, where they form cross-cutting crenulations. Often the earliest crenulations have the smallest wavelengths and the last the largest. There are always at least one more deformation event, and one more folding set, than the number of sets of crenulation present.

Cleavages and their associated folds are given different notations depending on the phase of deformation that produced them. The folds formed by the first phase of deformation are termed F1 folds, whilst those produced by the second phase of deformation are termed F2 folds. Cleavages are denoted by the letter S for surface, thus slaty cleavage is termed S1 since it usually forms in the first phase of deformation, whilst crenulation cleavages must be S2 or higher numbers. Bedding is denoted by S0.

Folds occur on a wide range of scales from crenulations up to structures many kilometres in wavelength. Smaller parasitic or minor folds occur on the limbs of larger-scale folds and have the same axial plane orientations. Minor folds, however, have different symmetries depending on where they are located on a larger fold. On the left limb of an anticline, for example, minor folds have a Z symmetry, whilst they have an S symmetry on the right limb. In the hinge region minor folds have M symmetries. The symmetry of minor folds is, therefore, useful in locating the fold axes of larger structures. Cleavages have the same symmetries as minor folds depending on their locations on fold structures. The symmetries of minor folds and cleavages are shown in Figure 5.4. Note that to observe the correct symmetry it is necessary to be looking down, rather than up, the hinge line of a fold if the hinge is inclined (plunging).

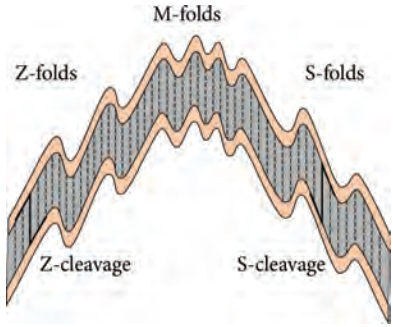

Figure 5.4 The relationship between the symmetries of minor folds and cleavage with major structures.

In metamorphic rocks, interpretation of structure can be greatly complicated by the tendency for bedding to become disrupted along its length owing to boudinage. This process occurs since the limbs of tight folds can become nearly perpendicular to the principle stress direction and can experience extension along their length. Competent beds, such as quartzite or marble, can separate into elongate sections called boudins, whilst more ductile beds, such as schist or phyllite, can thin and flow into the space, or neck, between the boudins. Similarly, thickening of beds occurs in the hinge region of folds. Quartz veins may also be located in boudin necks where pressure solution causes redistribution of quartz from high stress to low stress regions. The formation of boudins is shown in Figure 5.5.

Boudinage can complicate the interpretation of folds in metamorphic rocks since it can prevent the limbs of folds being traced along their length. Some features of boudinage are, however, useful. Boudin necks, for example, are parallel to the hinge-line of the folds that formed them. Boudins also tend to preserve fold hinges allowing these fold closures to be recognized by their characteristic shape.

Finally, beds can be overturned if they are on the lower limb of a large recumbent fold. Way-up is thus an important feature to record within metamorphic rocks. Sedimentary structures such as cross-bedding, mud-cracks, and ripple marks can be preserved in quartzites interbedded with either phyllites or schists.

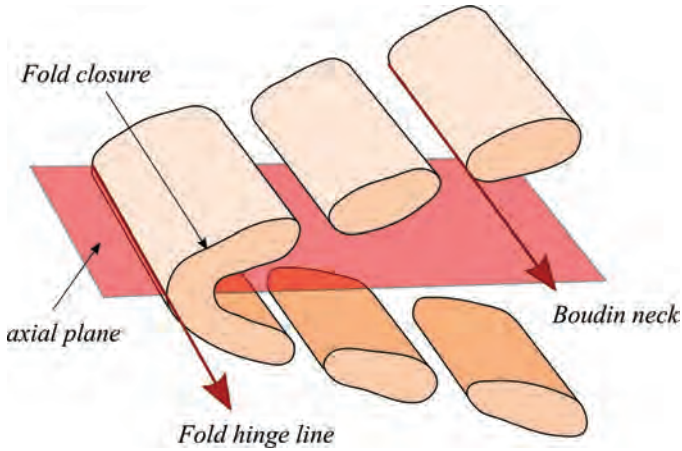

Figure 5.5 Showing boudins and their spatial relationship with folds of the same generation. Boudin necks are broadly parallel to the hinges of the folds that formed them.

5.2 Field sketch of fold interference in schists

Folds within schists of the Moine Supergroup from Glenfinnan in Scotland are shown in Figure 5.6 together with a worked example of a field sketch. The first task in drawing is to identify the most important features to be drawn. In metamorphic rocks, however, this task is made more difficult by their complexity. Some simple methods make it easier to identify the key structures.

The best way to find folds in metamorphic rocks is to look for fold hinge regions (fold closures) since these tend to stand out owing to their characteristic shapes. Two obvious fold closures appear in this photograph where the quartzite beds wrap back on themselves and form isoclinal folds with interlimb angles of <5°. Both exhibit significant thickening of the quartzite bed in the hinge region since quartzite is relatively ductile during amphibolite facies metamorphism. The fold axial trace of both folds runs along their line of symmetry and is shown in Figure 5.6b. It cannot be traced much beyond the quartzite beds. As in Chapter 4 for simple folds, the interpolated fold axial trace can be drawn onto the field sketch as a guide.

Since both folds are isoclinal these may be first generation F1 folds. This can be confirmed by their axial planar slaty cleavage formed by the alignment of mica minerals. The photograph in Figure 5.6a doesn't have

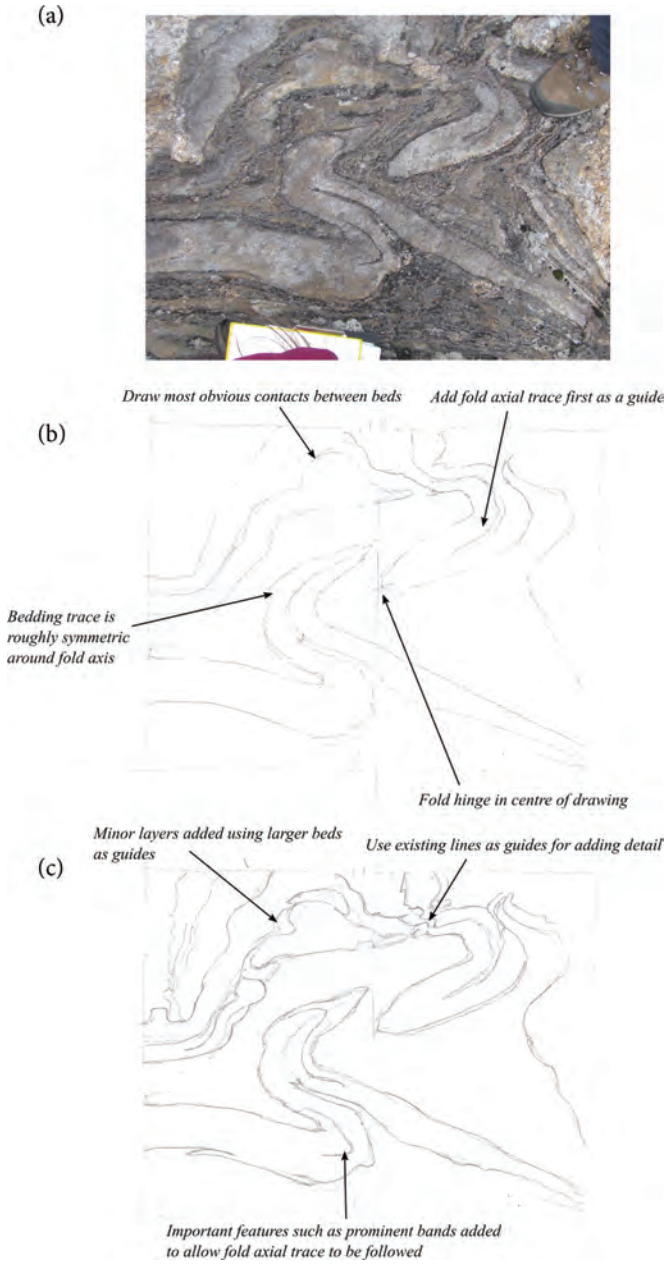
(a)
(b)
Draw most obvious contacts between beds
Add fold axial trace first as a guide
Bedding trace is roughly symmetric around fold axis
Fold hinge in centre of drawing
(c)
Minor layers added using larger beds as guides
Use existing lines as guides for adding detail
Important features such as prominent bands added to allow fold axial trace to be followed

Figure 5.6 Initial stages of a field sketch of fold interference in the Moine Schist at Glenfinnan in NW Scotland.

the resolution to show individual crystals of biotite and muscovite, however, in the field a slaty cleavage can be found in the hinge region of these folds. Often the slaty cleavage is best preserved in the hinges of tight folds whilst elsewhere it is disturbed by later, superimposed crenulation cleavage. Identifying cleavage orientations in the field frequently involves getting noses up against rocks.

Following the F1 fold axial traces reveals that they are curves rather than straight lines and thus have been deformed around later folds. The shape of these folds is more open with an interlimb angle of ~30° and they are probably F2 folds. Their axial planes run slightly off the horizontal line of the diagram and thus trend almost left to right.

Crenulations can be seen folding the mica minerals in the schist bands in the outcrop, their axial traces also run left to right, close to the horizontal line. Since they are almost parallel to the axial traces of the F2 folds these are likely to be S2 crenulation cleavage.

Now that the two sets of folds have been identified, the over-all pattern of the quartzite beds can be seen to form a type 3 fold interference figure (Figure 5.3). This indicates that that the F1 and F2 folds are co-axial, meaning that their hinge lines are parallel, even if their fold axial planes are at an angle to each other. Often F1 and F2 folds in mountain belts are nearly co-axial.

Once the folds have been identified, the area to be drawn to best show the fold interference pattern can be chosen, and the size of the drawing selected (half a page in a notebook). Blocking-in this sketch is relatively easy since the exposure is flat and in plan view. The quadrant system introduced in Chapter 3 allows the important features to be positioned, which are the boundaries of the quartzite beds and the interpolated fold axial traces, as shown in Figure 5.6b. Further detail necessary to illustrate the fold axial traces can now be added, such as laminations in the quartzite beds that wrap around the folds (Figure 5.6c).

The schist bands in this outcrop are challenging to draw owing to large number of small-scale features they contain. Only a small proportion of these can be added to the sketch and it is necessary to be selective and to simplify the geology. In this case there are thin quartzite bands in the schist that give an indication of bedding and help trace fold axial planes from the quartzite into the schist—these have been added to Figure 5.7a.

The final details to include in this sketch are the cleavages since these are parallel to fold axial traces. Cleavage is difficult to draw in field

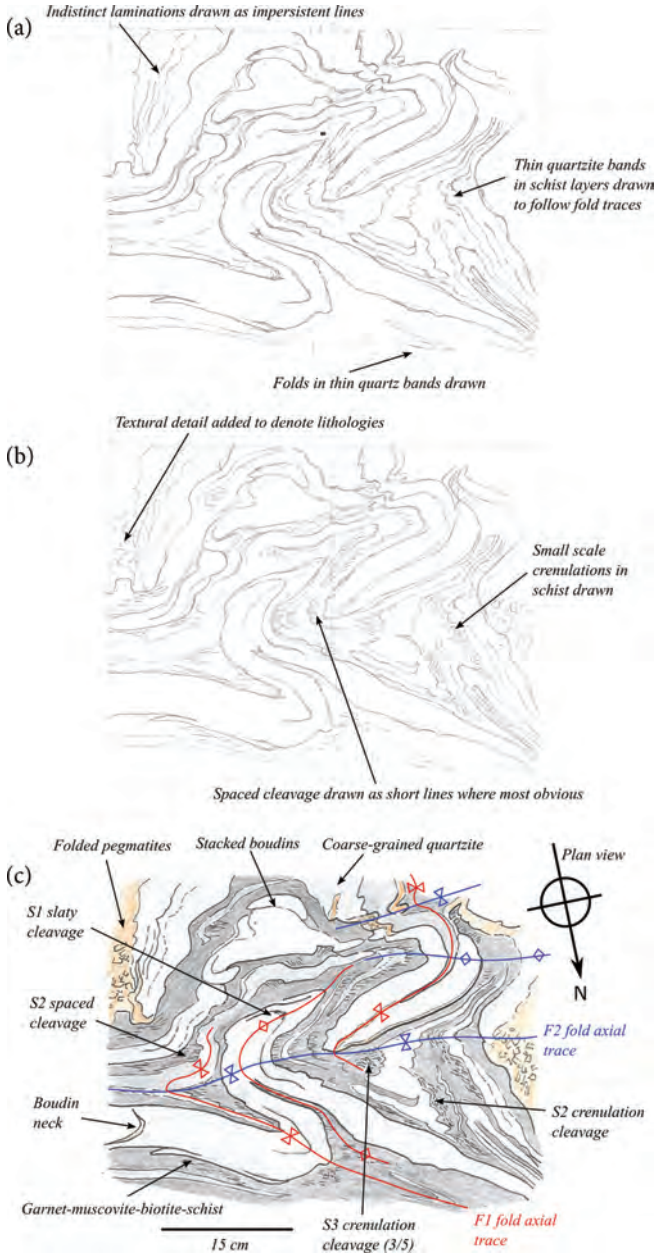

Figure 5.7 Final stages of a field sketch of fold interference in the Moine Schist at Glenfinnan in NW Scotland.

sketches since it is a small-scale feature and is often present throughout most of the rock. It is, therefore, not possible to draw cleavage everywhere that it occurs. A good compromise is to add cleavage to a sketch where it is most apparent and as realistically as is possible; although it will always be slightly schematic. In Figure 5.7b cleavage has been added in selected areas that best illustrate its spatial relationships with the folds. An important observation in the current sketch, made whilst drawing cleavage, is that some crenulations are not parallel to the F2 fold axial traces and thus may indicate the presence of a third phase of folding.

The last task is to interpret the sketch by drawing fold axial traces and adding descriptive labels, as shown in Figure 5.7c. Coloured ink can be used to distinguish fold axial traces from other lines and standard symbols used for synforms (converging arrows) and antiforms (diverging arrows). Since this outcrop is exposed on a horizontal surface, and is thus in plan view, an arrow labelled with north can be used to indicate direction.

5.3 Sketch of folds in gneiss

High grade metamorphic rocks are often intensely deformed and have numerous sets of superimposed folds making individual phases of folding more difficult to identify. Folds within an outcrop of Lewisian Gneiss from NW of Loch Inver in Scotland are shown in Figure 5.8 together with a worked example of a sketch. The large folds in the outcrop have clearly defined axial traces that can be included in the blocking-in stage of drawing to help guide the geometry of the structures (Figure 5.8b).

During the drawing process fold closures with orientations that are nearly parallel to the limbs of the larger structures are noticed suggesting they are an earlier generation of minor folds. They are parallel to some of the metamorphic banding suggesting they are F2 folds, since banding often forms parallel to crenulation cleavage. However, F2 and F1 folds are likely to have been rotated to near parallel orientations by such intense deformation. These features are added to Figure 5.8c.

The felsic bands in the gneiss are important to record accurately in the sketch since they exhibit significant variation in thickness owing to ductile flow into the hinge regions of folds and owing to the formation

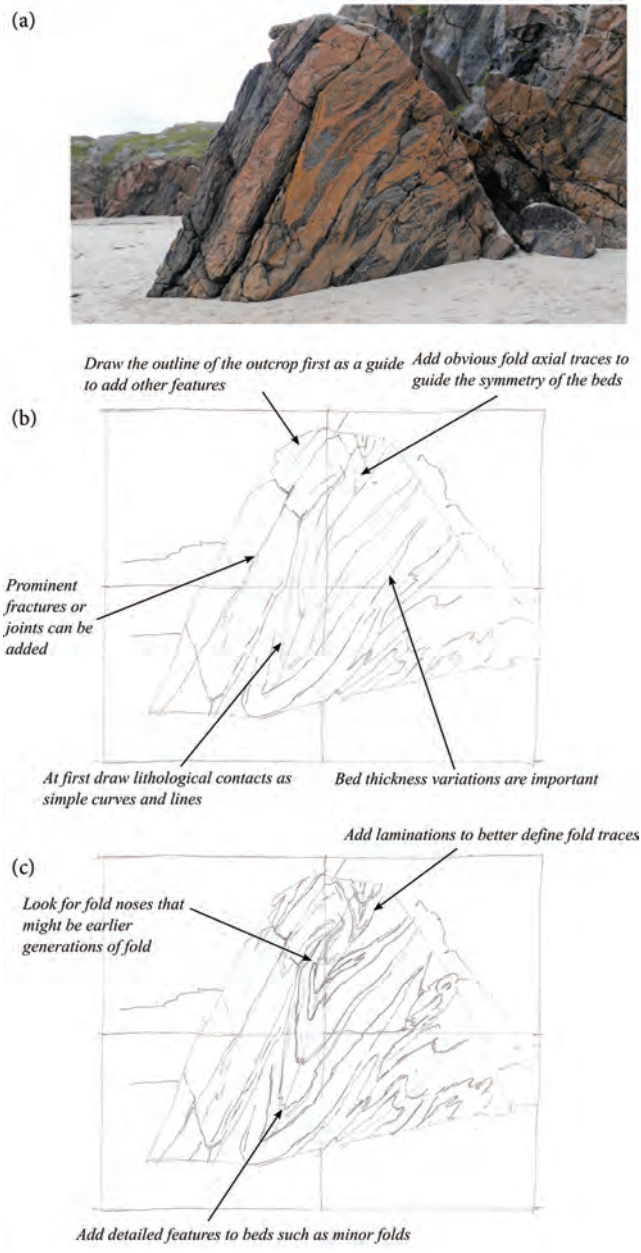
(a)
Draw the outline of the outcrop first as a guide to add other features
Add obvious fold axial traces to guide the symmetry of the beds
(b)
Prominent fractures or joints can be added
At first draw lithological contacts as simple curves and lines
Bed thickness variations are important
Add laminations to better define fold traces
(c)
Look for fold noses that might be earlier generations of fold
Add detailed features to beds such as minor folds

Figure 5.8 A sketch of folds within Lewisian Gneiss, NW of Loch Inver (photo credit: Daniel Burgess).

of boudinage. Finally, a gentle curvature in the felsic bands, that also deflects the fold axial traces of the large fold structures, is likely to indicate a later generation of F4 open folds. These features are all interpreted in Figure 5.9.

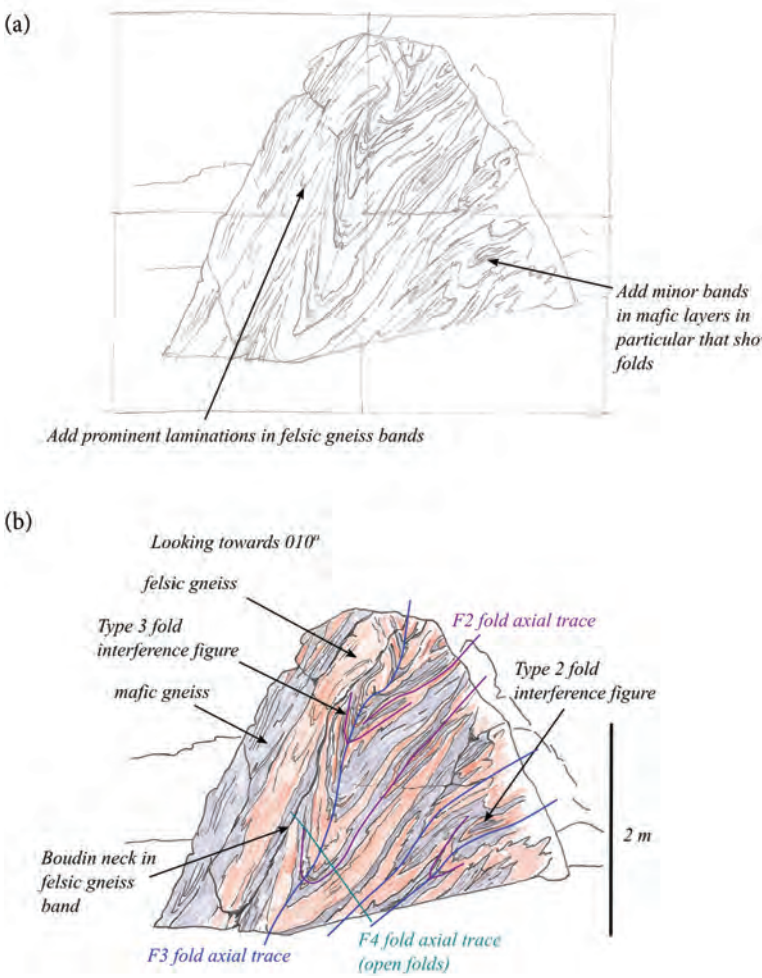
(a)
Add minor bands in mafic layers in particular that show folds
Add prominent laminations in felsic gneiss bands
(b)
Looking towards 010°
felsic gneiss
Type 3 fold interference figure
mafic gneiss
F2 fold axial trace
Type 2 fold interference figure
2 m
Boudin neck in felsic gneiss band
F3 fold axial trace
F4 fold axial trace (open folds)

Figure 5.9 Final stages of a sketch of superimposed folds in Lewisian Gneiss at Loch Inver in Scotland.

5.4 Folds within phyllite

Phyllites can pose a particularly difficult subject for a field sketch when they contain thin laminations of metasiltstone—a common occurrence when their protoliths were distal turbidites. Although phyllites are often less intensely deformed than schists or gneisses the difficulty in observing bedding in thinly laminated rocks, over-printed by prominent cleavage, makes it difficult to identify folds and renders them difficult to draw.

Often in phyllites open folds, with wavelengths of less than a metre, are the most obvious and dominate outcrops. Folds are usually most easily seen when looking along their hinges. A useful approach is, therefore, to view outcrops from different directions to locate folds in different orientations. Frequently the most obvious folds within phyllites have axial planes parallel to the best developed crenulation cleavage and are most commonly F2 or F3 folds.

Phyllites formed during the Hercynian orogeny in Sardinia are shown in Figure 5.10. Colour differences between the black phyllite bands and the grey metasiltstone beds can be used to trace bedding (S0) and show a change in orientation between the upper right and the rest of the image. The change in orientation is the result of an open F2 fold and is associated with an axial planar, spaced cleavage. Tracing some of the metasiltstone laminations along their lengths reveals some closures of isoclinal folds with fold axial traces almost parallel to bedding, these are F1 folds. Sketching these structures involves drawing enough of the metasiltstone bands to allow the folds to be seen, however, it is necessary to be selective since there are too many laminations to draw them all. Particularly important are the F1 fold closures. All these features can be included in the blocking-in phase together with the prominent quartz veins (Figure 5.10b). The quadrant system, allows the positioning of features in the sketch.

Cleavage and some additional siltstone beds can be added after blocking-in to provide detail to the key features. Only a small proportion of the cleavage should be drawn and in areas where it is most prominent. In this exposure the spaced S2 cleavage does not change orientation and is, therefore, not deformed by later folds (Figure 5.10c). Slaty cleavage, formed by the alignment of mica crystals, is often impossible to see in photographs, but can be observed on the rock, sometimes requiring the use of a hand lens to be seen. Where such ultrafine detail

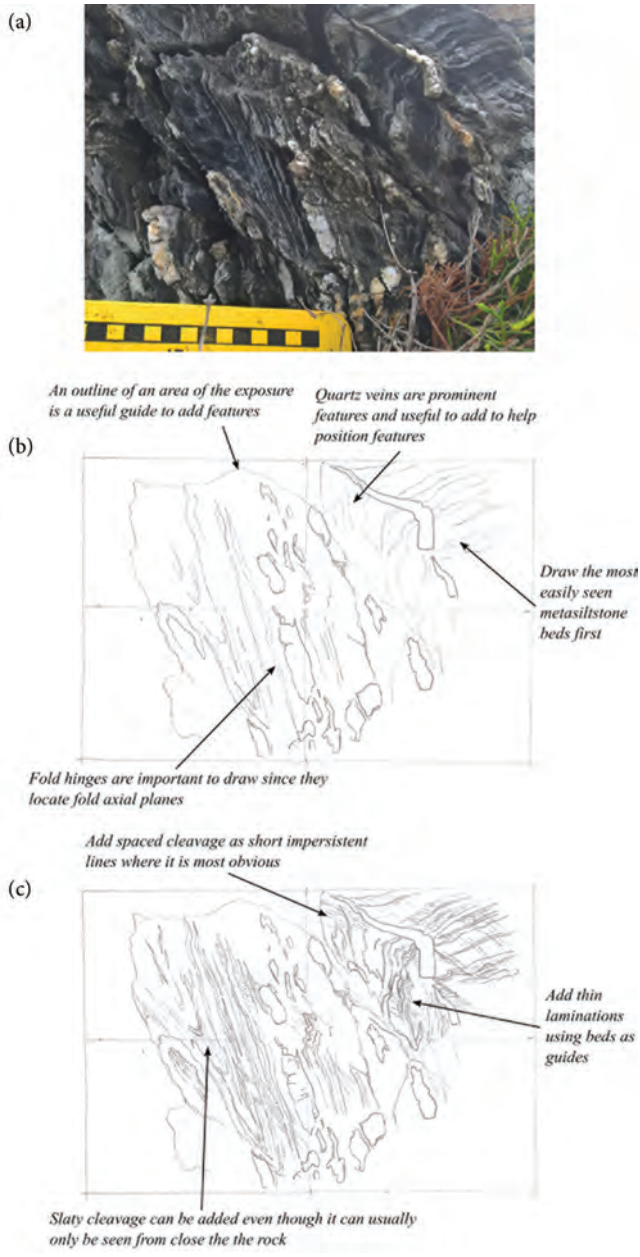
(a)
An outline of an area of the exposure is a useful guide to add features
Quartz veins are prominent features and useful to add to help position features
(b)
Draw the most easily seen metasiltstone beds first
Fold hinges are important to draw since they locate fold axial planes
Add spaced cleavage as short impersistent lines where it is most obvious
(c)
Add thin laminations using beds as guides
Slaty cleavage can be added even though it can usually only be seen from close the the rock

Figure 5.10 Folds within phyllite from the Nurra Coast of Sardinia.

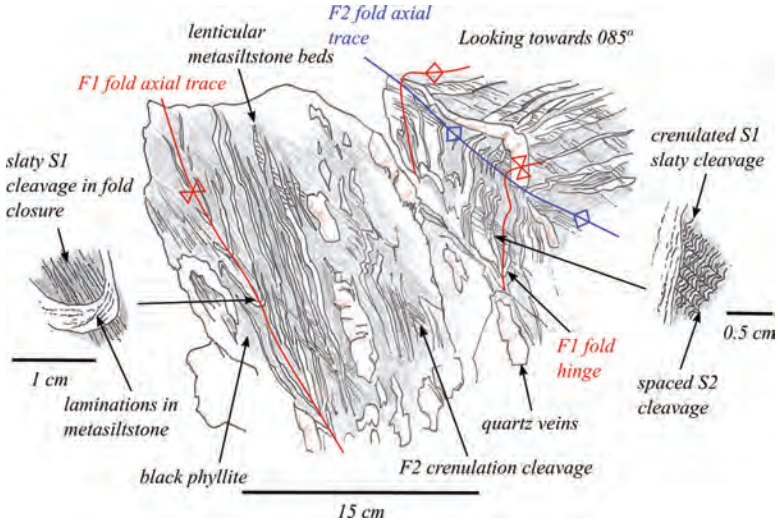

Figure 5.11 A finished sketch of folds within phyllite showing the use of peripheral diagrams to illustrate ultrafine detail.

exists, small peripheral diagrams can be added around the edge of the sketch to illustrate the spatial relationships. In this example two peripheral sketches have been added to Figure 5.11 to show the geometrical relationship between slaty cleavage, crenulation cleavage and bedding in two locations. Notice each diagram has its own scale and is labelled. Peripheral diagrams are useful in sketches of a wide variety of geology and are discussed again in Chapters 8 on igneous rocks and Chapter 9 on sedimentary rocks.

5.5 Common mistakes

5.5.1 Imprecise bed or banding thickness

Within metamorphic rocks bed thickness may initially appear random; however, usually changes in bed thickness occur owing to ductile flow, with thickening at fold hinges and thinning on fold limbs. Bed thickness is important to record accurately because it often has a structural significance. For example, a fold in a quartzite bed that thins at its hinge is likely to be a later generation of fold. The thinning at the hinge has

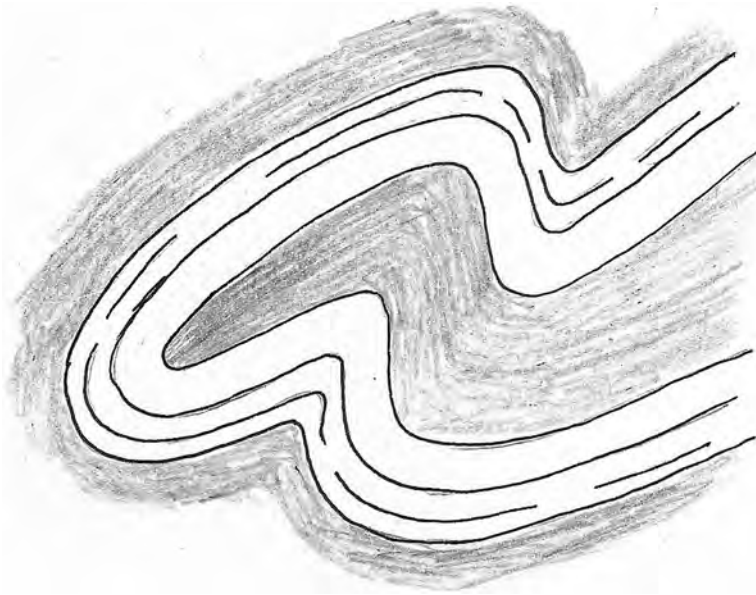

Figure 5.12 A sketch showing incorrect bed thicknesses.

probably been inherited from pre-existing boudinage generated during earlier folding. A common mistake in drawing complex structures is to try and draw beds with a constant thickness or to add changes in thickness in the wrong place. In this example (Figure 5.12) a constant thickness has been drawn and is a case of drawing an expectation rather than an observation.

5.5.2 Schematic cleavage

Cleavage is often difficult to draw when it is small in comparison to the size of the sketch. A common mistake is to draw cleavage as a series of schematic parallel lines. Although cleavage is often moderately regular it is rarely present as equally spaced, parallel fractures. Cleavage is also usually better developed in some places than others; often in fold closures. Although some degree of simplification is required in drawing cleavage, realism is also needed. Figure 5.13 shows a sketch of folds with schematic cleavage.

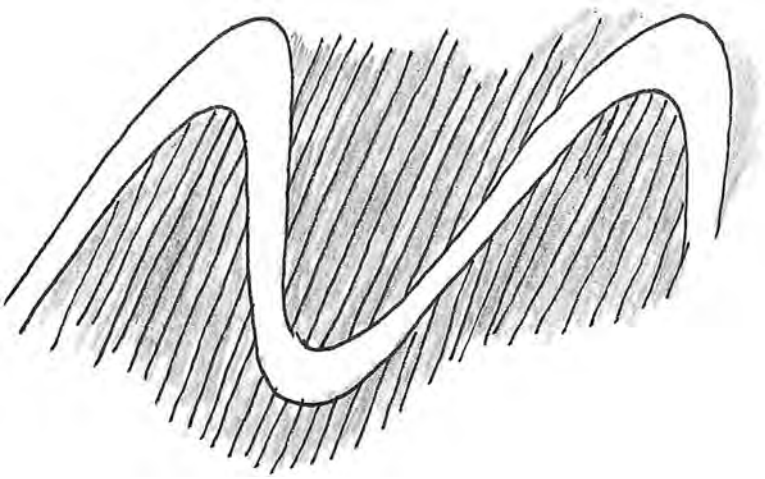

Figure 5.13 A sketch of folds with schematic cleavage.

5.6 Key concepts

Important concepts that apply to drawing metamorphic rocks are:

- Spend extra time assessing the structures to identify the key features to be drawn.
- Use fold axial traces drawn on the sketch to guide the geometry of folds.
- Take care in reproducing bed thickness accurately since it often has a structural significance.
- Draw cleavage where it is most apparent.
- Annotate the diagram with fold axial traces.

6

Drawing three dimensions

Most outcrops are not simple flat surfaces and have relief. The three-dimensional (3D) nature of the world around us makes drawing even simple geology difficult since it means there are few straight lines or simple curves. On a 3D outcrop, planar beds can appear folded if their trace is exposed on an undulating surface. When an outcrop consists of several bluffs or headlands, in contrast, the bedding trace is deflected from one to the next in a manner that resembles faults. Perspective too influences how the geology appears. A bed of constant thickness will appear to become thinner with distance. Perspective also changes the orientation of parallel bedding planes making them appear to pinch into the distance.

In this chapter an approach to drawing 3D outcrops is described that involves simply drawing what is seen. The problem is that our minds are designed to interpolate what we see into a 3D mental landscape and thus our interpretation of observations is fundamentally creative at an instinctive level. The best approach in drawing a 3D object, however, is to attempt to draw the shapes and lines as we see them, without the filter provided by our mental rendering engine. Essentially we must take what we see and visualize it as a two-dimensional (2D) image, rather than a 3D set of surfaces. This is very different from conventional art technique where perspective is often an artificial construct.

6.1 Perspective

Understanding perspective is important in drawing geology, if mainly to understand why irregular 3D surfaces influence the shapes seen in two dimensions. It is important since we have the natural ability to see the trace of a planar feature on a curved surface and to automatically realize that the feature is a plane. The temptation is, therefore, to try and draw what is known to be there. The feature is planar, thus its line of intersection is erroneously drawn straighter than it should be.

Geological Field Sketches and Illustrations: A Practical Guide. Matthew J. Genge, Oxford University Press (2020).
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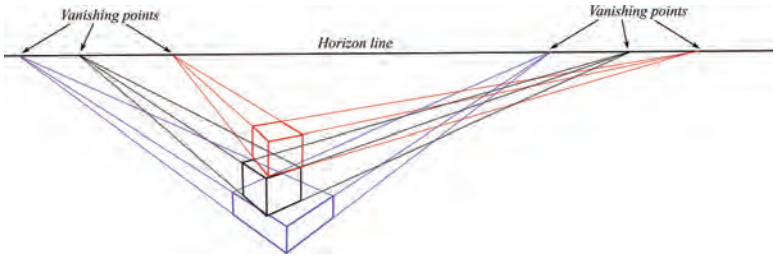

Figure 6.1 Illustrating the use of vanishing points to draw a series of cubes.

Although in sketching outcrops the concepts of perspective are not employed, it is useful to know some of the important points about drawing in a perspective view. Any 3D object with parallel lines, for example, the edges of a cube, will appear to converge with distance from the viewer. If these lines are extrapolated to infinity, they will converge to a single position known as the vanishing point. Horizontal straight edges on an object will have a vanishing point that lies upon the horizon. A cube has two sets of parallel edges and thus two vanishing points.

Vanishing points can be used to draw 3D objects by extending tie lines from the point through the object. Numerous vanishing points are needed to draw all the parallel sets of lines, as shown in Figure 6.1. In geological sketches, however, vanishing points are not used since these diagrams are not constructed from the imagination and instead are drawn using observation.

6.2 Drawing small outcrops with relief

Many small natural outcrops have significant relief, often with competent beds forming step-like features. Drawing such outcrops is difficult because the perspective of the exposure obscures the relevant features and geometries that should be drawn. In the field our inherent ability to see features in three dimensions as surfaces allows us to interpolate their geometry, whilst in a photograph or sketch their form becomes less clear. In the example in Figure 6.2 a minor fold in quartzite beds at Kinlochleven in Scotland is shown. The beds extend towards us making them appear to thicken and distort the simple geometry of the fold.

To draw an outcrop in which perspective has a significant affect involves visualizing the outcrop as a 2D image. Where the 3D nature of

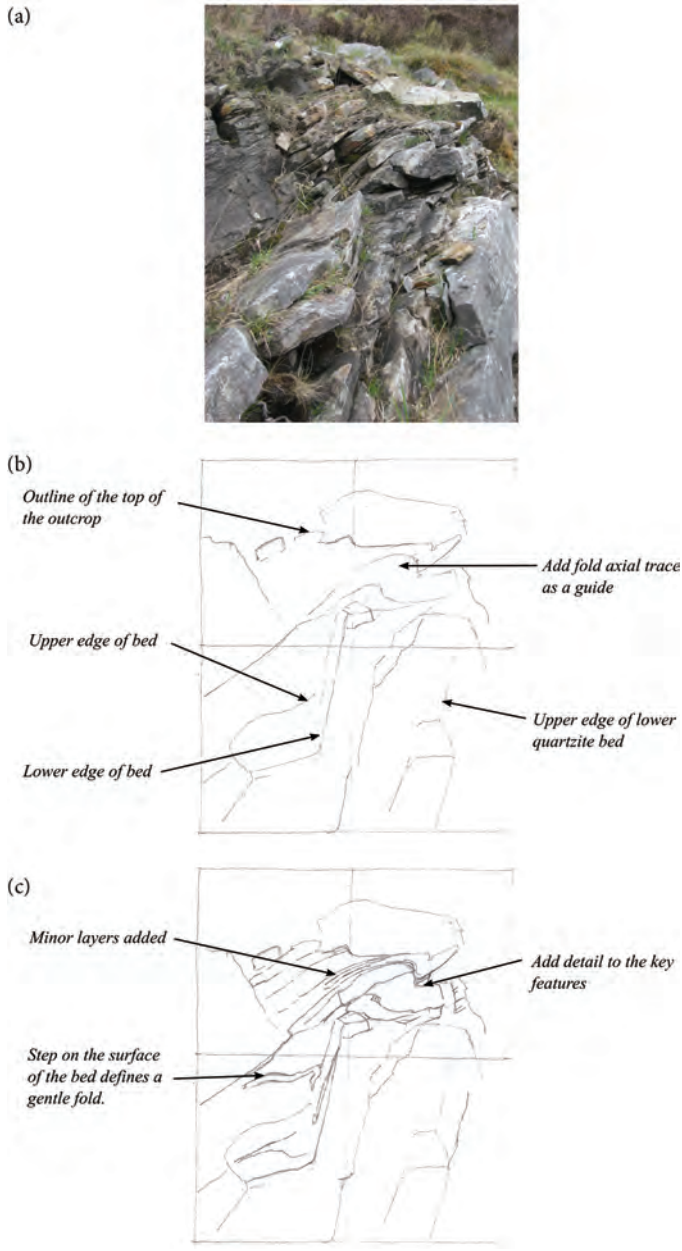
(a)
(b)
Outline of the top of the outcrop
Add fold axial trace as a guide
Upper edge of bed
Upper edge of lower quartzite bed
Lower edge of bed
(c)
Minor layers added
Add detail to the key features
Step on the surface of the bed defines a gentle fold.

Figure 6.2 Blocking-in and essential detail stages of a field sketch of a small outcrop with folds from Kinlochleven in Scotland.

the outcrop becomes important is in the choice of the important lines to draw. Here it is the upper and lower intersections of the bedding surface with joints, since these mark the top and bottom surfaces of these layers as well as defining the geometry of the fold.

As in all sketches it is necessary to evaluate the geology—here a minor S-fold is exposed at the top of the exposure—it is S since the folds are plunging towards us, thus its apparent Z symmetry is reversed. The important lines are those that outline the fold and its left limb, which forms a large bedding surface that extends towards the viewer. The upper and lower edges of the bed extend from just above the centre of the image towards the lower left corner, with a step in the foreground. Notice that the upper and lower edges appear further apart in the foreground than in the distance as a result of perspective. They may be positioned using the quadrant system with particular attention paid to the angles of the lines relative to the horizontal. As in Chapters 4 and 5, fold axial traces can be drawn to assist in accurately recording the geometry of the fold, as shown in Figure 6.2b.

Once the most important lines have been drawn they can be refined by adding details, such as important fractures and adjacent beds. There are several features on the beds that help define the 3D nature of the exposure. A step on the top of the quartzite bed, to the left of the centre of the image, is particularly important since it defines the shape of a gentle parasitic fold, as shown in Figure 6.2c. This feature was only noticed during drawing.

The final phase of the sketch is to add additional relevant detail. Steps in the schist band are important in showing its relief. Lineations on the upper surface of the quartzite bed help emphasize the fold on its surface and can be exaggerated a little to demonstrate its geometry. Vegetation, such as grass, can also be included in a sketch to show the nature of the exposure as a small outcrop on a grassy slope. Grass can be drawn quickly as a line with irregular zigzag-like shapes. Too much time shouldn't be devoted to drawing vegetation.

The last tasks in constructing this drawing are to add labels, annotations and colour. In sketches showing outcrops with significant relief, colour can be used to emphasize shape as well as lithology. Shading can be used sparingly to emphasize volume by adding darker colour where the surface is less exposed to light, such as within inner corners and fractures. Often it is best not to try and reproduce the complexity of shadow on an outcrop, which is a function of light angle, since deep

shadows tend to obscure detail. Shading is, therefore, somewhat schematic. It is better to use colour for shading than parallel ink lines.

In diagrams of objects with significant relief, scale changes with distance from the viewer. A good approach to applying a scale to such drawings is to draw a scale bar at an important position to illustrate the size at a specific distance from the viewer. In Figure 6.3b the scale bar has been positioned adjacent to the fold. Notice that measurements have

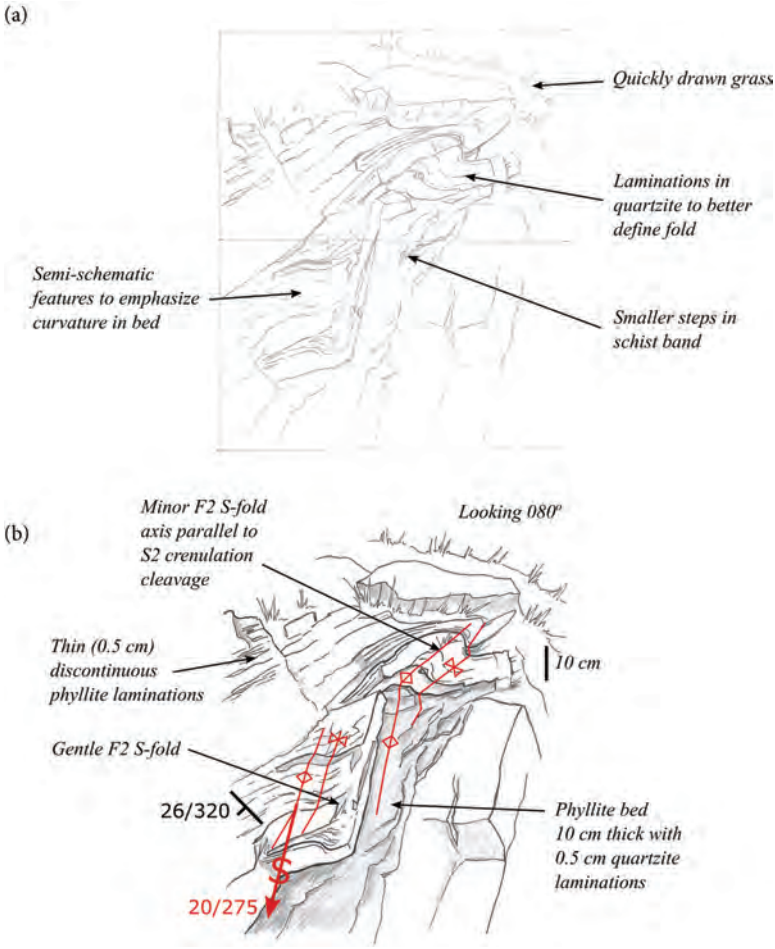
(a)
Quickly drawn grass
Laminations in quartzite to better define fold
Semi-schematic features to emphasize curvature in bed
Smaller steps in schist band
(b)
Minor F2 S-fold axis parallel to S2 crenulation cleavage
Looking 080°
Thin (0.5 cm) discontinuous phyllite laminations
10 cm
Gentle F2 S-fold
26/320
Phyllite bed 10 cm thick with 0.5 cm quartzite laminations
20/275

Figure 6.3 Additional detail and the final sketch of an outcrop containing minor folds from Kinlochleven in Scotland.

been added as symbols to this diagram to show exactly the location where they were taken.

6.3 Sketching large 3D outcrops

Large outcrops can also have significant relief, often due to differential weathering and erosion, with competent beds forming prominences compared with softer rocks. Owing to their size, large outcrops often have more complex geometries than smaller exposures and are usually more difficult to draw. Stair Hole in Dorset in the UK (Figure 6.4) is a good example of differential erosion where the competent Portland Limestone forms a prominent ridge compared with the interbedded mudstones and limestones of the Purbeck Group. This locality is well-known in the UK and exposes a series of folds known as the Lulworth Crumple within the Purbeck strata.

Blocking-in the shape of Stair Hole is crucial in drawing an accurate sketch of the locality. The best approach is to initially draw the outline of the outcrop as simplified straight lines that will then be used as guides to add more detailed features. The start and end points of each line can be positioned using the quadrant system as a guide. The highest point on the headland, for example, is just to the left of the horizontal centre line and dips to the left, ending about half way down the upper quadrant. To the right of the highest point, the line made by the cliff face drops away steeply towards the right and then runs along the top of the Portland Limestone reaching the bottom of the upper quadrant, as shown in Figure 6.4b.

Details on the outline of the exposure such as indents along the top of the Portland Limestone and the caves on the lower side can be added using the original straight lines as guides. To help position features on the outline temporary marks can be drawn as vertical strokes to visually test their position (Figure 6.4c). These are particularly useful where two features are present at the same horizontal or vertical position, or when features have a quasi-regular separation.

Adding geological features to this sketch can be achieved by drawing on fold axial traces to guide the geometry of folds. Some repositioning of lines will be necessary during this process to ensure the shape of the folds and thicknesses of beds are accurate. Bedding traces are also present on the prominence made by the Portland Limestone and help define the 3D shape of the outcrop. The most obvious of these planes are added to Figure 6.5a.

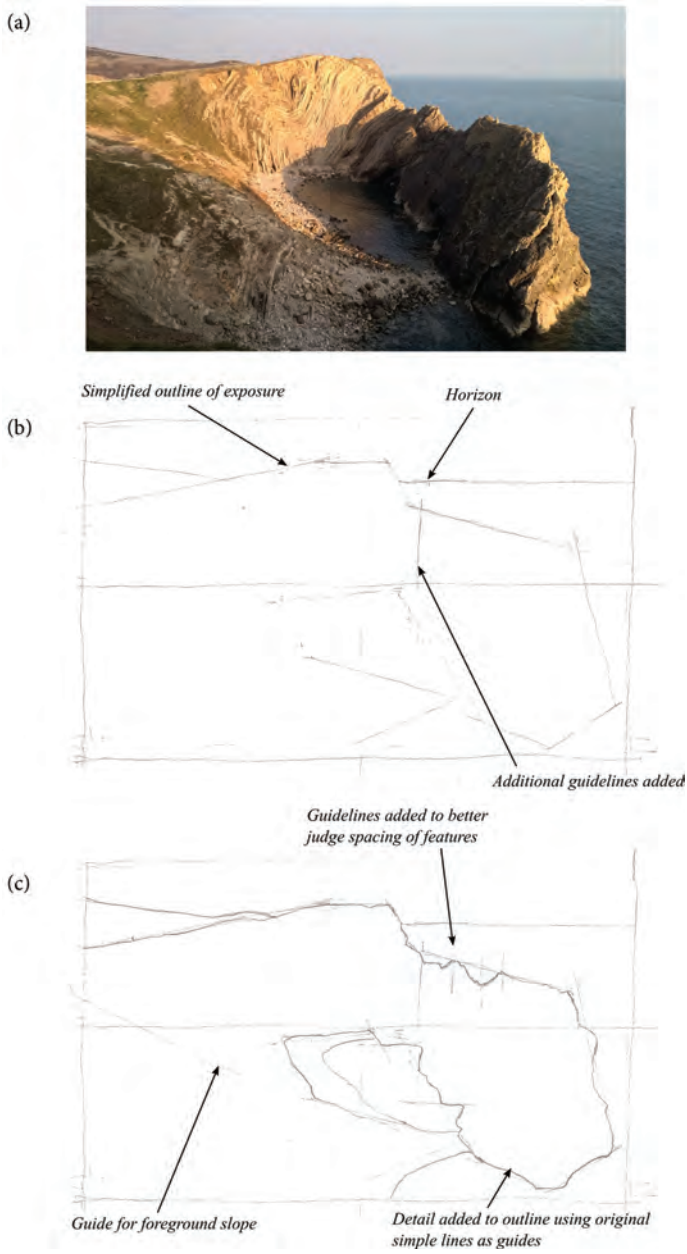

Figure 6.4 Blocking-in of a field sketch of Stair Hole in Dorset, UK.

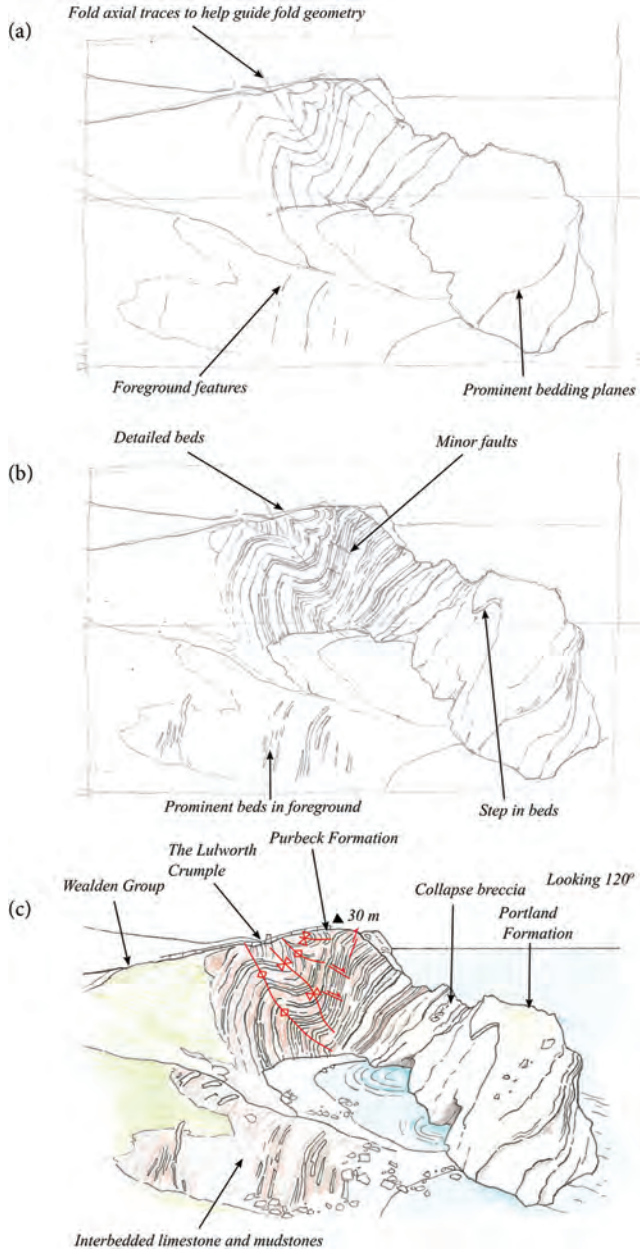

Figure 6.5 Illustrating the addition of detail, colouring, and annotation of a field sketch of Stair Hole in Dorset, UK.

Additional features can now be added to the sketch. Particularly important is the pattern of bedding within the Purbeck Group where packets of thin limestone beds are present within mudstone. Care taken in drawing these features enables stratigraphic information to be recorded. Several small minor faults will also be noticed whilst drawing the beds since they are found to be discontinuous and displaced along their length. Beds on the prominence of the Portland Limestone are less obvious but several discontinuous traces can be seen—one has a noticeable step-like feature where a bed has been truncated by erosion. This feature defines the topography of the prominence and is thus useful to draw (Figure 6.5b). Some lithological information can also be included. A layer containing large clasts, for example, appears at the top of the Portland Limestone and is a collapse breccia formed by dissolution of evaporites.

Colour is useful in this sketch in illustrating the lithologies present; however, some subtle shading can be added to emphasize the shape of the outcrop. Although somewhat unnecessary, boulders can be added to the beach and ripples to the surface of the water to reinforce the 3D nature of the caves, as shown in Figure 6.5c.

6.4 Drawing coastal cliffs

Often when cliffs are located on the coast they must be drawn when viewing along them, owing to lack of a better place to stand. Perspective has a significant effect on the appearance of cliffs viewed in this orientation due to the decrease in apparent height and bed width with distance. Bluffs along cliffs produce numerous local horizons when viewed along their length at which bedding appears to suddenly change in position and in width. Bluffs on cliffs, therefore, appear to be discontinuities that resemble faults at which bedding are displaced.

The coastal cliff at West Bay in Dorset, UK (Figure 6.6) exposes the Jurassic Bridport Sands and is an excellent example of why the perspective of cliffs can make them difficult to draw. The beds here are nearly horizontal and consist of alternating layers of cemented and unconsolidated sandstone that are most easily seen in this image at the base of the cliff in the foreground. Further along the cliff the beds become difficult to see.

Rather than trying to artificially account for the change in scale an approach in which each part of the cliff is drawn as observed will result

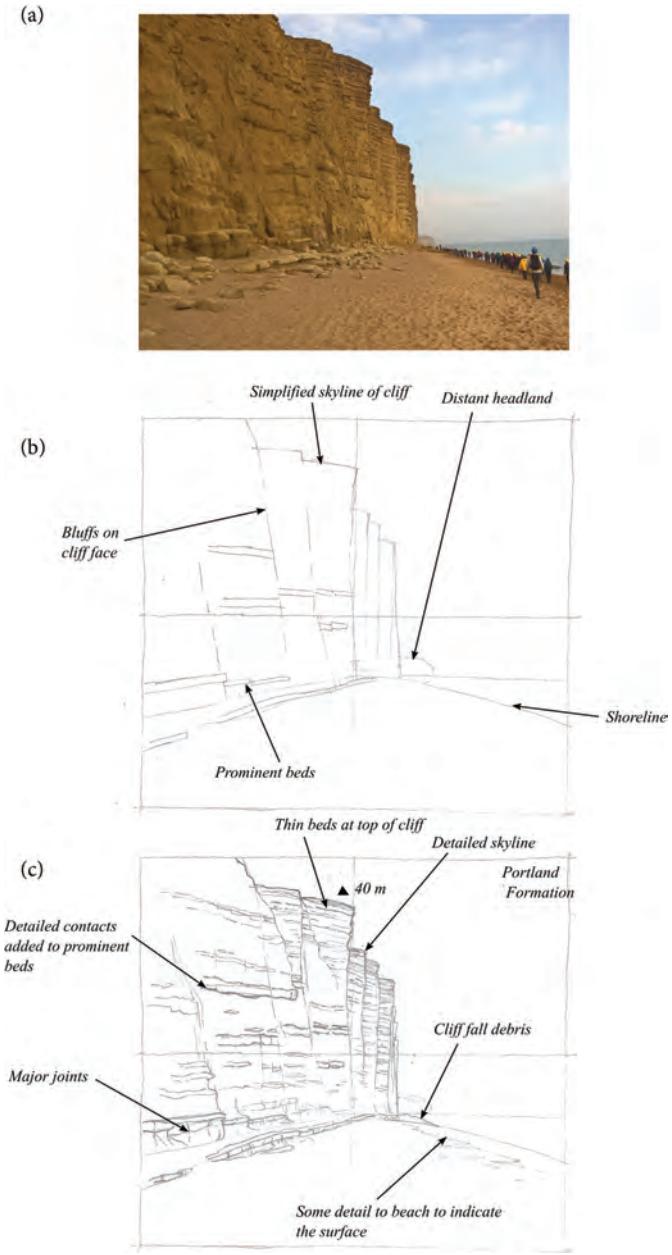

Figure 6.6 Blocking-in and initial detail addition to a field sketch of the Bridport Sands in Dorset, UK.

in a much more accurate sketch. Perspective views always require careful blocking-in to ensure each part of the drawing has the correct scale from the start. In this example the top of the cliff appears as line with several steps, each segment located over a bluff—these can be drawn as straight lines using their positions relative to each other and the quadrants to locate them on the page. The local horizons made by each bluff can also be drawn down from the steps in the skyline to divide the cliff into several portions. Drawing the base of the cliff and several of the most prominent beds completes blocking-in and provides a good base onto which details can be added (Figure 5.6b).

In this sketch the most important geological features are the cemented beds that protrude slightly from the cliff owing to their competent nature. Their quasi-regular spacing and variable thickness are important to record in the drawing. Some are also discontinuous laterally, disappearing after only a short distance. Note that the cemented layers become more closely spaced and thinner towards the top of the cliff.

An important consideration in drawing the sequence is the correlation of beds between different segments of the cliff as bounded by bluffs. A useful approach is to work on each segment separately and position cemented layers in one segment relative to those already drawn. In the distant areas, only a proportion of the layers can be drawn. A prominent bed at the bottom of the cliff also extends for a significant distance and can also be added, as shown in Figure 6.6c.

Additional features to add to the sketch include furrows on the surface. Although these represent weathering features, and have little geological significance, they allow the geometry of the cliff face to be represented more accurately. Some lithological features can also be shown on the surface of the cemented beds in the foreground, such as weathering pits corresponding to differences in cementation owing to bioturbation (Figure 6.7).

The final sketch can be coloured to show differences in lithology. In this example the colours used are exaggerated to emphasize the different beds. Finally, labels, a scale, and a looking towards direction should be added. A scale could be given at a particular location; however, since perspective results in a significant variation in scale, a spot height provides some indication of the size of the cliff.

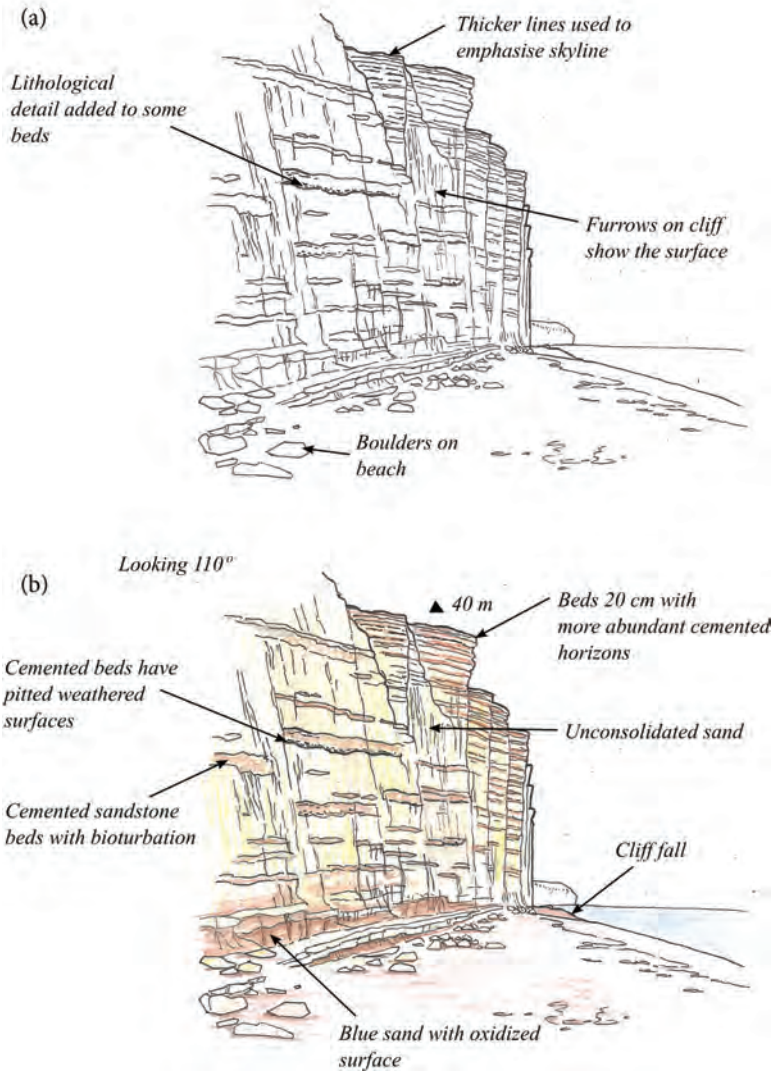
(a)
Thicker lines used to emphasise skyline
Lithological detail added to some beds
Furrows on cliff show the surface
Boulders on beach
(b)
Looking 110°
▲ 40 m
Beds 20 cm with more abundant cemented horizons
Cemented beds have pitted weathered surfaces
Unconsolidated sand
Cemented sandstone beds with bioturbation
Cliff fall
Blue sand with oxidized surface

Figure 6.7 The final stages of a field sketch of the Bridport Sands from Dorset, UK.

6.5 Common mistakes

6.5.1 Exaggerated perspective

Probably the most common mistake made in drawing outcrops with significant relief is to exaggerate perspective resulting in poor geometric relationships. This example (Figure 6.8) shows the folded quartzite locality used in Figure 6.2. The quartzite beds and the folds have been drawn as rectangular blocks with unnatural looking geometry. Often such sketches stem from an attempt to draw what is expected, rather than what is seen. Exaggerated perspective diagrams are reasonable records of the geology but lack in accuracy and lead to simplification of details.

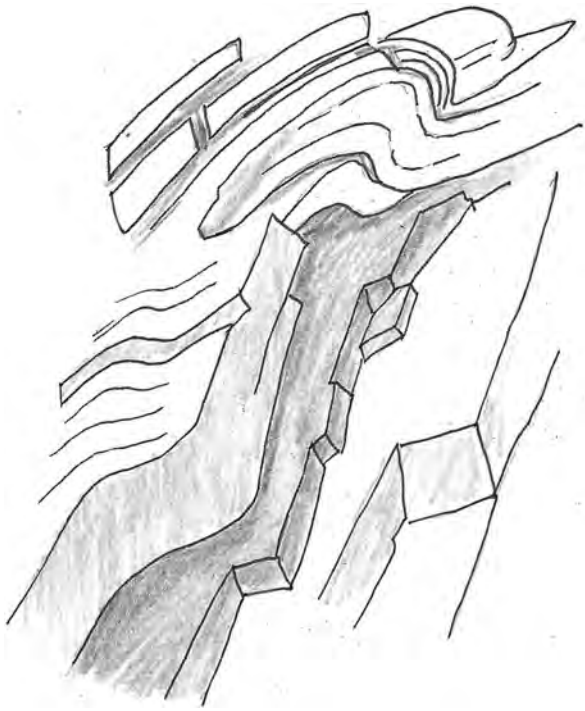

Figure 6.8 Illustrating exaggeration of perspective in a field sketch.

Figure 6.9 Showing a sketch using line shading.

6.5.2 Line shading

A common technique in line art is to use closely spaced lines to shade areas of a drawing. Although a valid method of recording lighting, and one commonly employed in illustrative art in geology, it introduces lines that do not exist in reality, as shown in Figure 6.9. These addition lines could be confused with features such as fabrics and lineations. When replaced by ink, line shadowing also tends to obscure detail and make the essential geological features less easily seen.

6.6 Key concepts

Important concepts that apply to drawing outcrops with relief:

- Imagine the field of view as a 2D image and do not artificially construct a perspective view.

- The edges between bedding planes and joints are important lines to draw to record the 3D nature of the exposure.
- Block-in the proportions and positions of features accurately. Correct geometry is vital in producing realistic sketches of 3D exposures.
- Subtle shading is useful in emphasizing the volume and shape of geological features seen in three dimensions.

7

Landscape sketches

Drawing landscapes is a highly useful activity in geology since it records the distribution of units across topography. This provides not only a means to predict the location of important boundaries, but also greatly assists the creation of cross-sections. Landscape sketches are particularly valuable when units can be distinguished at a distance allowing 'alpine mapping'. However, they can also record stratigraphic variations, in particular lateral variations, and the nature of large-scale structures. Photographs of a landscape are usually a poor substitute for a field sketch since often the features that allow units of rocks to be identified from a distance are subtle and easy obscured by vegetation and drift cover. Frequently features in landscapes that seemed obvious in the field are almost impossible to see within a photograph.

In this chapter, methods to draw sketches of the geology in landscapes are described. An approach in which the view is subdivided into areas of differing scale by drawing local horizons is adopted. Geological features are added to these areas using horizon lines as guides to their position and scale. Minor topographic elements, such as ravines and gulleys, are used to emphasize the three-dimensional surface of topography. Finally, an outlining technique is presented to enable sketches of landscape covered with vegetation to be drawn accurately.

7.1 Drawing multiple horizons

Often landscape drawings are made difficult by the presence of numerous horizon lines that subdivide the field of view into regions with different ranges of scale. An example of a landscape with several horizons is shown in Figure 7.1, which is a view of the volcano Kerimasi in the East African Rift in Tanzania. The most distant feature is the volcano and is several kilometres away. Closer to the viewer are two cinder cones, one in the centre of the image is seen as a conical hill, and

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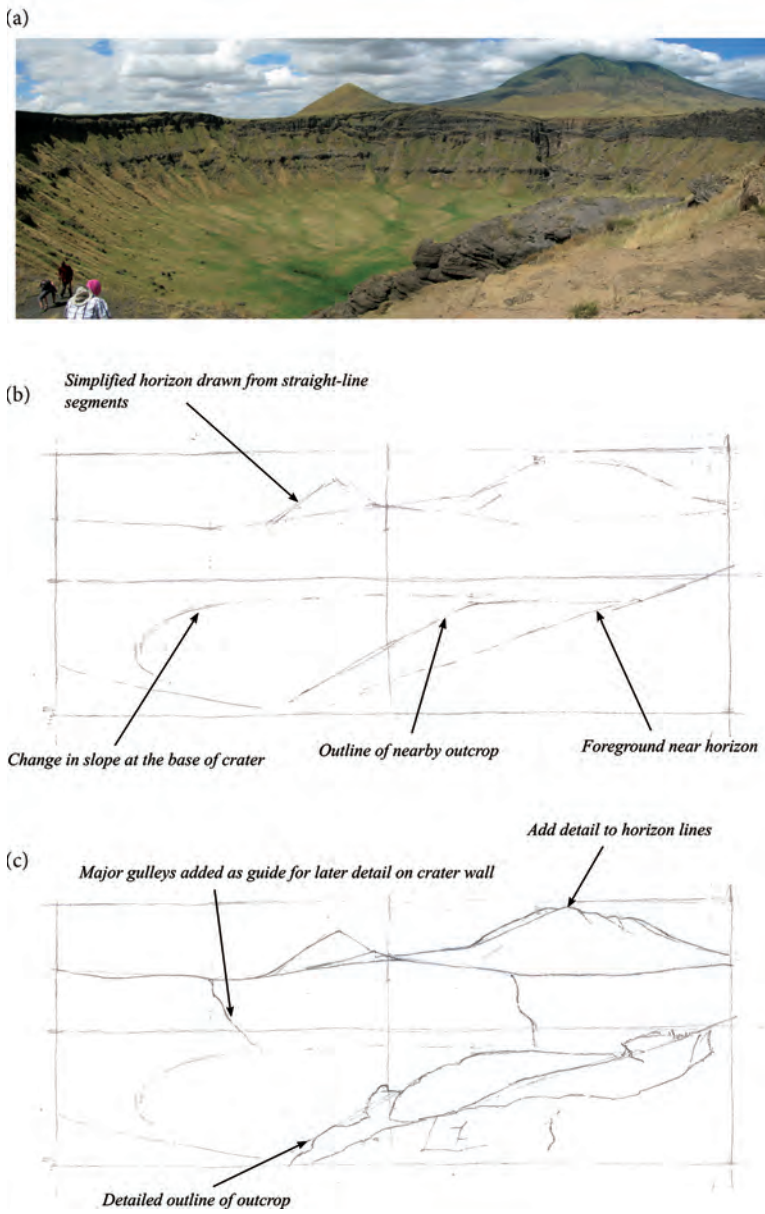
(a)
(b)
Simplified horizon drawn from straight-line segments
Change in slope at the base of crater
Outline of nearby outcrop
Foreground near horizon
(c)
Add detail to horizon lines
Major gulleys added as guide for later detail on crater wall
Detailed outline of outcrop

Figure 7.1 Initial stages of drawing of Kerimasi volcano in Tanzania.

one in front of Kerimasi appears as a low, wide cone. Both cinder cones are bounded by local horizons where scale changes abruptly. Taking up much of the image, and the main subject of the photograph, is a phreatomagmatic crater around 800 m in diameter and 100 m deep. The distant rim of the crater forms a sub-horizontal, but undulating, horizon. Finally, in the foreground is the nearside rim of the crater with an outcrop of pyroclastic rock that forms another local horizon. Each of these horizons delimits regions of the sketch that show different features.

A landscape sketch begins with the three rules. First decide how much of the landscape needs to be drawn, which usually depend on what is the subject of the sketch. In this case the purpose of the drawing it to record the volcanic sequence exposed on the wall of the crater and its proximity to Kerimasi and the nearby cones. Choosing a wider field of view is always tempting for a landscape sketch, for example, the entire geometry of the crater could be drawn; however, increasing the width will decrease the resolution of detail that can be included. A useful rule of thumb in drawing landscapes is to choose a field of view that is small enough that the head need not be turned to see it all comfortably. In this case the field of view of the photograph is appropriate for the purposes of the drawing since it includes all the important geological features.

When drawing landscapes additional observations beyond the geology are required. The important horizons need to be identified since these will form areas of the drawing with different levels of detail and scale. It is, therefore, required to assess the topography as well as the geology.

During blocking-in the first features to add to a landscape sketch are the horizons. Since horizon lines are often complex with many undulations and small-scale features, it is best to initially simplify them as a series of straight lines that define their general trend, as shown in Figure 7.1b. The advantage of this approach is that the start and end point of the straight-line segments can be accurately positioned by reference to the quadrants ensuring that there is a geometrically correct framework for the rest of the sketch. Often it is useful to begin adding detail to the horizon lines before adding the important geological features since the topographic details make it far easier to position these objects. Details such as large gulleys can also be added as simple lines, as shown on the crater wall in Figure 7.1c.

The most prominent geological features, such as the major contacts between units can then be added to the sketch using the horizons and the topographic detail to help position them. In this case there is a grey bedded unit that makes up most of the top of the crater wall and an underlying layer of interbedded grey and ochre beds. Several prominent thicker grey layers are present in this lower sequence and are discontinuous along their length. Finally, a thin ochre unit is present at the very top of the crater sequence and is the same layer as in the foreground. Simple lines can be added to the drawing to guide the positions of these prominent boundaries (Figure 7.2a).

Once the geological boundaries have been added to the sketch, details such as bedding can be drawn. The upper grey layer has visible bedding traces that pinch and swell to create dune-like features—such large-scale cross bedding in pyroclastic deposits are usually formed by pyroclastic surges commonly associated with phreatomagmatic eruptions (see Section 8.4). The discontinuous nature of grey beds within the lower part of the crater sequence can also be drawn. These layers vary in thickness along their length to generate elongate lenticular bodies and may be the deposits of pyroclastic flows that are often restricted by topography. The beds cannot be followed over their entire lengths since they are obscured in places by scree and vegetation. Discontinuous lines can be used to convey where they are partially exposed. Since these are prominent layers and have shadowed overhangs at their base, thicker lines can be used to emphasize them. Some bedding traces can also be seen on the grassy slopes on the crater wall and on the cinder cones in the background but cannot be traced far laterally, these can be added as short parallel discontinuous lines. Finally, lithological features such as clasts and laminations can be added to the outcrop in the foreground of the sketch, as shown in Figure 7.2b.

Although all the geological elements have now been added to the drawing there are some additional topographic features that could be included. The slope of the crater wall, for example, can be indicated by including the trend of minor gulleys as lines. An irregular outline is also made by change in vegetation at the base of the crater and emphasizes the topography of the surface. Gulleys can also be added to the slopes of the volcano Kerimasi in the distance to give it volume and shape. Even though these additional topographic features are mostly ancillary, recording them can prove to be useful since in the absence of

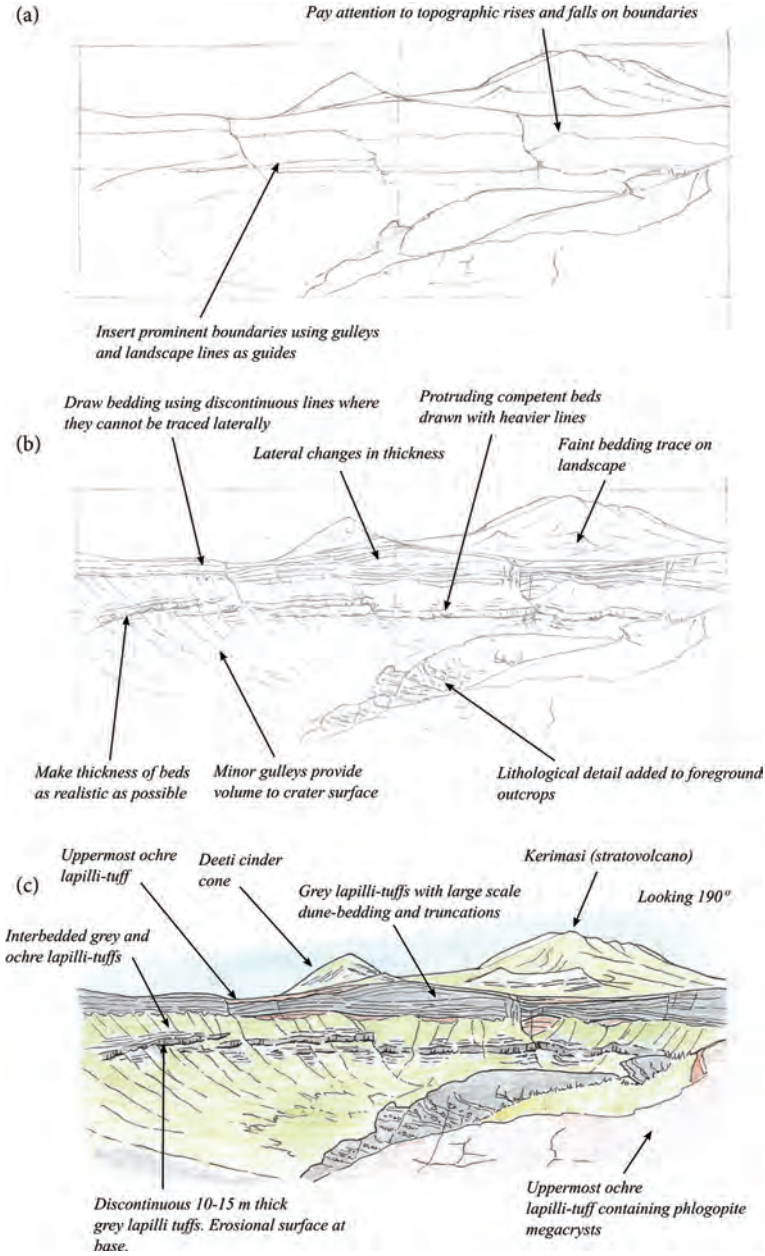
(a)
Pay attention to topographic rises and falls on boundaries
Insert prominent boundaries using gulleys and landscape lines as guides
(b)
Draw bedding using discontinuous lines where they cannot be traced laterally
Protruding competent beds drawn with heavier lines
Lateral changes in thickness
Faint bedding trace on landscape
Make thickness of beds as realistic as possible
Minor gulleys provide volume to crater surface
Lithological detail added to foreground outcrops
(c)
Uppermost ochre lapilli-tuff
Deeti cinder cone
Kerimasi (stratovolcano)
Looking 190°
Grey lapilli-tuffs with large scale dune-bedding and truncations
Interbedded grey and ochre lapilli-tuffs
Discontinuous 10-15 m thick grey lapilli tuffs. Erosional surface at base.
Uppermost ochre lapilli-tuff containing phlogopite megacrysts

Figure 7.2 The final stages of drawing of a sketch of Kerimasi.

a high-quality map they can be used to navigate and find routes to descend into the crater.

The final stage of every sketch is to label with scale, looking direction and descriptive labels. The latter can include lithology notes in addition to observations on structures and sequence (Figure 7.2c).

7.2 Sketching mountainsides

The steep slopes of mountains provide natural cross-sections through geology that often reveal the tectonic structure of an area as well as exposing sections through a sedimentary sequence. Drawing the geology exposed on mountainsides is, therefore, often worth the time involved. In Figure 7.3 a mountainside in Aliaga in Spain is shown that exposes a sequence of Jurassic and Cretaceous limestones and mudstones. The strata are located on the eastern side of an anticline whose axial plane trends parallel to the valley in the foreground. Several smaller folds can be seen on the mountainside and have axial planes that are almost perpendicular to the large anticline. These folds are superimposed structures originating from a second phase of deformation. Particularly interesting is the presence of disharmonic folds that have different wavelengths from one unit of strata to the next. The structure exposed on the mountain thus provides useful constraints on the wider regional geology and is worthy of sketching.

Drawing geology on mountains is complicated by their significant topography and by the large areas of rock they expose. Topography is easily over- or under-exaggerated without careful assessment of its dimensions. The large areas of exposure on mountains makes drawing difficult owing to significant number of features that could be included, thus it is necessary to be highly selective in what to draw.

The horizon formed by mountains is best simplified during blocking-in as straight-line segments that are more easily positioned. In this example the outline of the mountain rises steeply from the gorge on the left to just under half the height of the mountain, it then rises at a gentle angle to a peak located approximately halfway across the right quadrant before falling away to the right. This simplified geometry is easy to draw along with some of the other prominent features such as the lowermost exposed rocks on the mountain side and the tree line that runs through the valley, as shown in Figure 7.3.

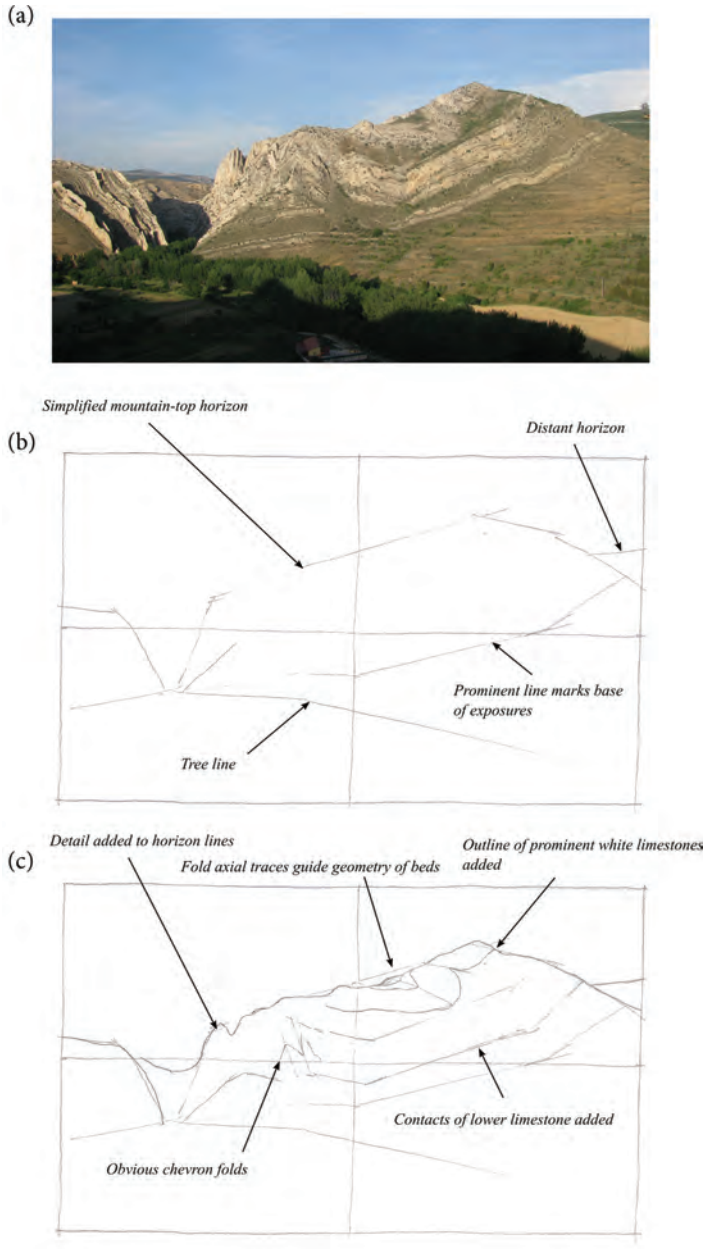

Figure 7.3 The initial stages of drawing of a mountainside in Aliaga, Spain.

The simplified outline can then be refined by adding details, using the initial lines as guides. The horizon along the top of the mountain, for example, has a prominent indent located right of the gorge, followed by a broad irregular set of crags and then a curved saddle leading to the peak. Accuracy in the placement of these more detailed features can be ensured by estimating their relative distance along the top of the mountain.

Geological features, such as the folds, can be added to the sketch using the detailed outline of the mountain as a guide to their positioning.

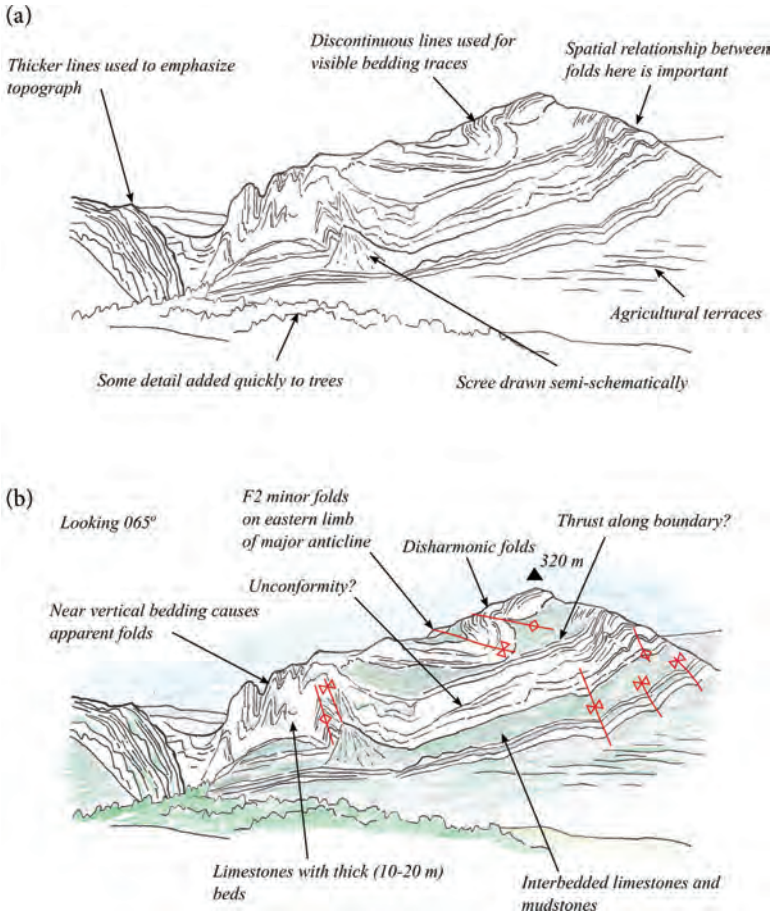
(a)
Thicker lines used to emphasize topograph
Discontinuous lines used for visible bedding traces
Spatial relationship between folds here is important
Agricultural terraces
Some detail added quickly to trees
Scree drawn semi-schematically
(b)
Looking 065°
F2 minor folds on eastern limb of major anticline
Disharmonic folds
Thrust along boundary?
320 m
Unconformity?
Near vertical bedding causes apparent folds
Limestones with thick (10-20 m) beds
Interbedded limestones and mudstones

Figure 7.4 The final stages of a sketch of a mountainside in Aliaga, Spain.

The axial trace of the synformal fold in the upper limestone beds, for example, intersects the horizon roughly in the middle of the broad saddle. Using the outline of the mountain to position features makes the sketch much more accurate.

The final geological details to be drawn are the bedding traces. Only the most prominent of the traces are included since there are too many to draw them all. Some features can also be drawn owing to their significance, even though they are subtle, for example, a truncation of bedding in the middle thick formation of limestones may suggest the presence of an unconformity (Figure 7.4a).

Ancillary details can be included if they require little time to add. A scree slope is present on the mountainside and can be represented semi-schematically using discontinuous lines to illustrate its surface. Agricultural terraces on the grassy slope to the right can be drawn as a reminder that there may be little exposure at this location. The tree line likewise can be added with some quickly drawn irregular zigzag lines.

Adding interpretative labels and annotations is the final task for this sketch. Some labels can be used to highlight more speculative interpretations rather than adding structural annotations. These would be useful if localities on the mountainside were visited. Colour also greatly helps with the clarity of the sketch since it highlights the lithological variation in the sequence.

7.3 Vegetated landscapes

Heavily vegetated landscapes pose difficulties in drawing since areas of trees or scrub hide the important geological features and make it difficult to correlate between individual exposures. A fold in El Pont de Suert in the Spanish Pyrenees is shown in Figure 7.5 and is only partially exposed on a wooded mountainside. The fold can be seen on a central exposure facing the viewer but is separated from several smaller outcrops by forest. The key to sketching such sparse outcrop is to draw the outlines of areas of exposure prior to adding the geological features they contain.

Like all landscape sketches the horizons present within the view provide a starting point during blocking-in and can initially be simplified as straight lines to aid accurate positioning. After enhancing the detailed features on the horizons, areas of exposure can be outlined to provide regions within which the geology can be drawn. There are two main

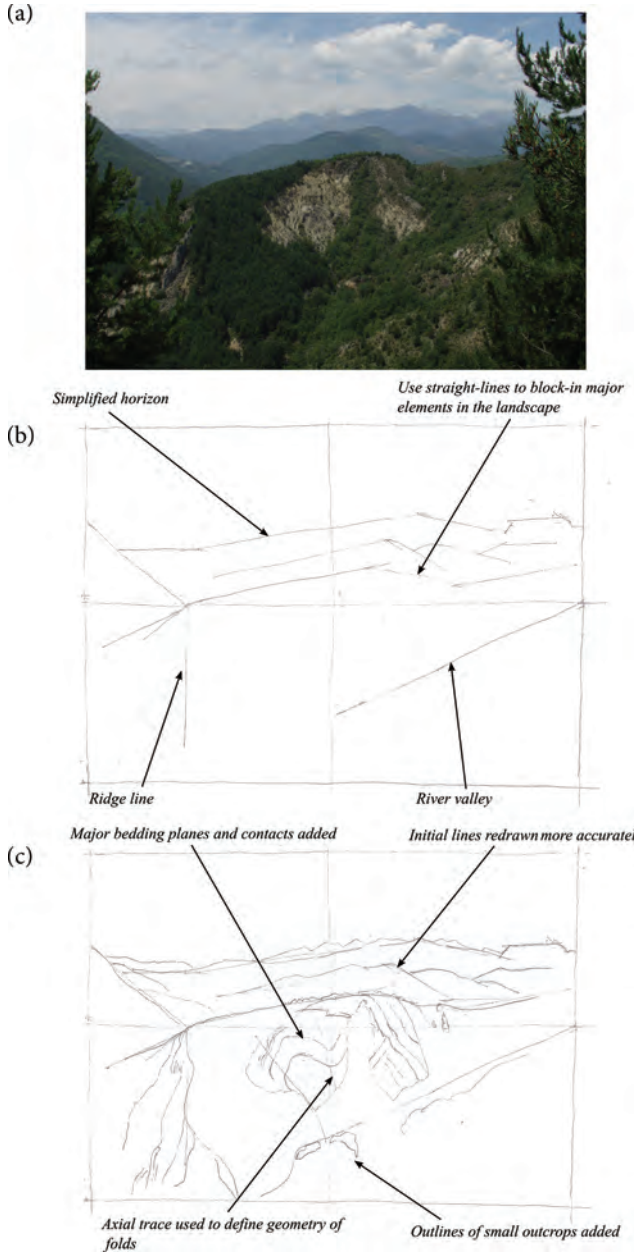

Figure 7.5 The initial stages of a sketch of a fold in El Pont de Suert, Spain.

units present within these areas, a dark-grey limestone, and an interbedded sequence of mudstones and siltstones containing sparse gypsum. The major boundaries between these units can be drawn within the areas of exposure. Drawing the fold axial traces observed in the central area of exposure greatly aids accurate representation of the

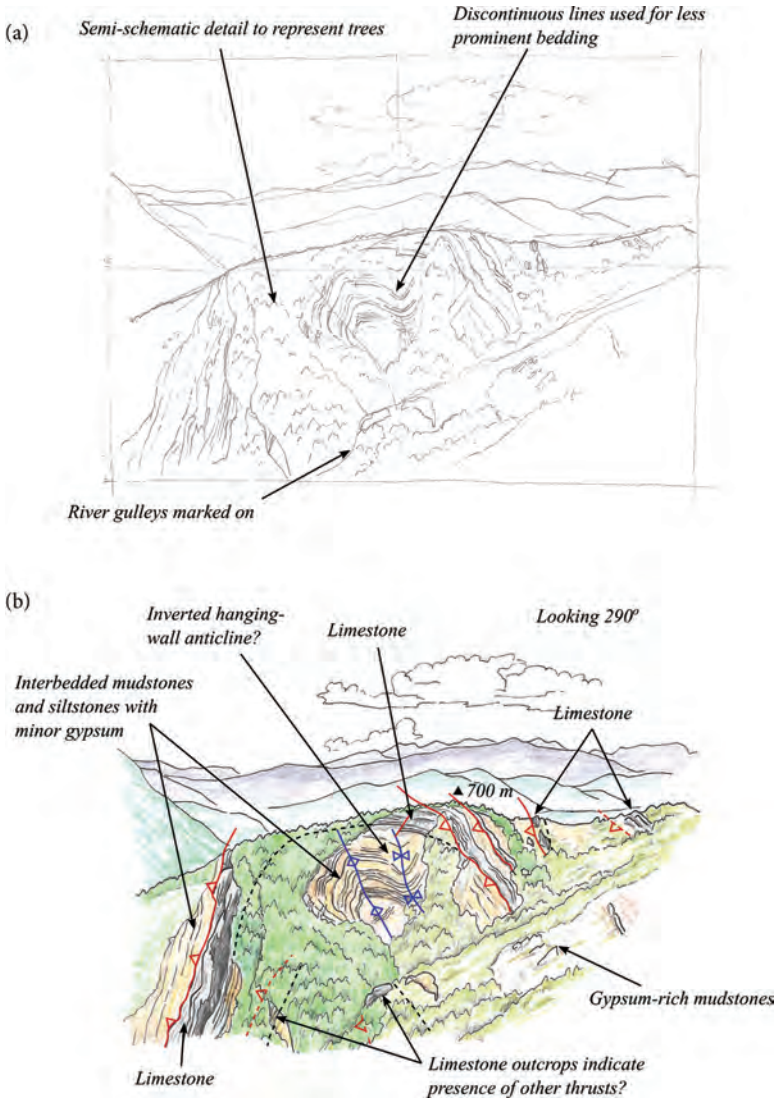

Figure 7.6 The final stages of a sketch of a fold in El Pont de Suert, Spain.

structure. Several smaller outcrops of limestone are also visible on the mountainside and can be drawn as outlined areas of realistic size and trend, as shown in Figure 7.5c. Once the overall framework of the sketch has been established relevant geological details such as bedding traces can be dawn since these emphasize the nature of the structure (Figure 7.6a).

Interpreting structure when exposure is limited is challenging. In this area the structure is dominated by a series of fold duplexes as part of an antiformal stack (Figure 7.7). The fold exposed on the mountainside is likely to be a hanging wall anticline that has been overturned, whilst the repeated appearance of the same limestone unit, with mudstones and siltstones in between, marks individual thrust duplexes. Similar geology is described in Section 14.2.2 on cross-sections. Annotations interpreting the locations of thrusts have been added to the completed field sketch in Figure 7.6b. Uncertain extrapolation of contacts through areas of no exposure can be added to such field diagrams using dashed lines. Often interpretations of landscape sketches

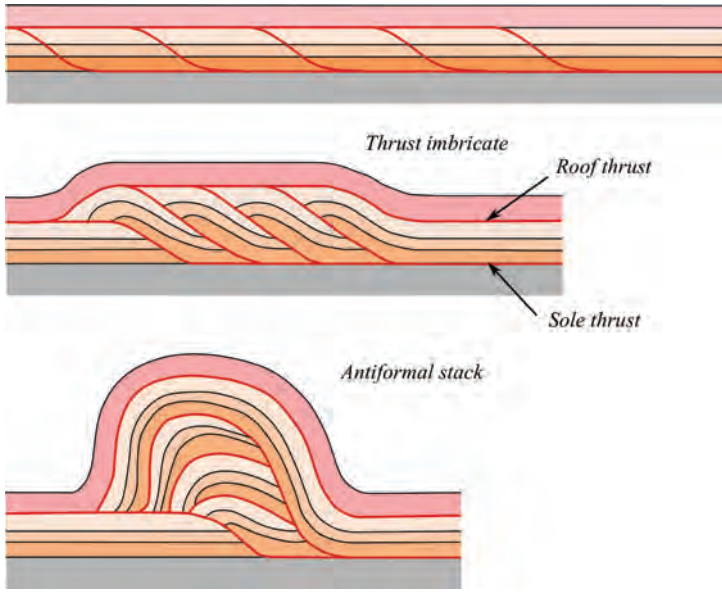

Figure 7.7 Illustrating the formation of an antiformal stack from thrust duplexes.

are tentative since they can expose geology that has yet to be visited and examined. Interpretation can, however, be updated once there is less uncertainty.

It is often useful when drawing vegetated landscapes to approximately represent the nature and distribution of vegetation since sketches can be useful in locating outcrops for closer inspection. Geology that can be seen easily from a good vantage point at distance often becomes impossible to see from nearby and a landscape sketch will provide a useful reference when traversing the sketched area. Drawing trees, however, isn't a good use of time; however, forested areas can be quickly added to sketches using irregular zigzag lines that give an impression of treetops. The most convenient scale to use in landscape sketches is a peak height obtained from a map.

7.4 Common mistakes

7.4.1 Insufficient detail

Landscape sketches that show only the outline of one hill or mountain and the orientation of bedding and structures are reasonable (Figure 7.8). However, the lack of topographic detail such as tree lines, gulleys, and scree slopes greatly reduces their value. Part of the reason for doing a landscape sketch is to show how the geology and topography intersect. The most prominent topographic features are, therefore, important to include.

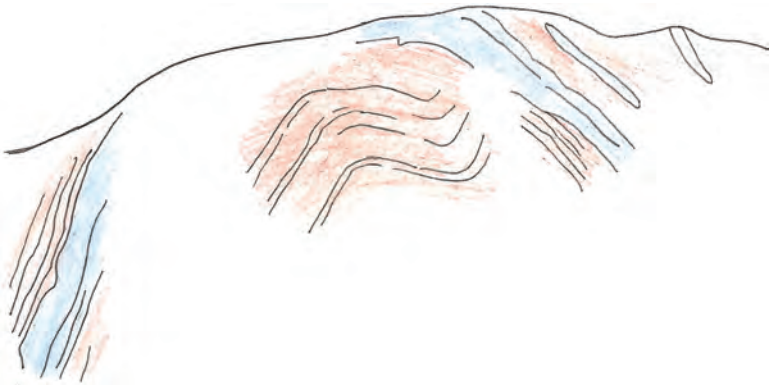

Figure 7.8 Illustrating a landscape sketch with insufficient detail.

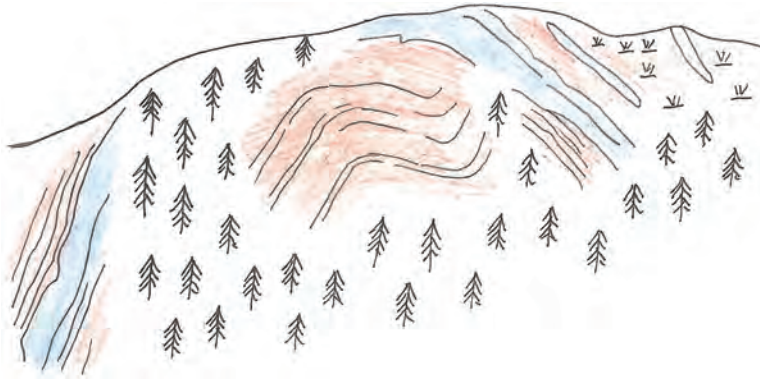

Figure 7.9 Showing a landscape using schematic vegetation.

7.4.2 Schematic vegetation

Vegetation such as trees, grass, and shrubs are small-scale features within landscape sketches and it is tempting to use schematic symbols to indicate their presence. This is entirely acceptable within a field sketch; however, the purpose of a symbol should be to simplify a sketch and reduce the time devoted to drawing. Sketches in which large numbers of schematic trees or grass symbols are used, as shown in Figure 7.9, are counterproductive since they take more time than drawing the trees more realistically.

7.5 Key concepts

In this chapter, several key concepts and methods were introduced:

- Accurate horizon lines are the key to an accurate landscape sketch and are easiest to draw initially as a series of straight-line segments.
- In sketches of landscapes where outcrops are difficult to see, for example, in vegetated terrains, careful observation is needed to evaluate their positions and bedding orientations.
- Topographic features such as ravines and ridges can be added as lines to give additional value to sketches of landscapes.
- Areas of exposure should be outlined and then in-filled with the geological features.
- Some indication of vegetation type can be useful in recording areas of partial or no exposure.
- Peak heights make useful scales in landscape sketches.

8

Drawing igneous outcrops

Igneous rocks form by cooling of magma on or below the Earth's surface, or as fragmental rocks generated by explosive volcanic eruptions. The important features to record within drawings of igneous outcrops, and the objective of field sketches of these exposures, vary depending on the type of igneous rock exposed.

The objective of sketches of intrusions, formed by cooling of magma in the sub-surface, is often to examine the mechanisms of intrusion or the relative timing of intrusive events. Sketches of intrusions, therefore, often focus on the shape of the igneous body, the nature of the contact with the surrounding country rock and the geometry of cross-cutting relationships. Details such as clasts of country rock (termed xenoliths), the alignment of crystals, and the presence of fine-grained chilled margins are also important to record.

Lava poses significant challenges in drawing. Lava flows have complex geometries and many detailed surface features that often reveal the nature and direction of flow. Small-scale features, such as vesicles and crystals, are also important in understanding the rheological behaviour of magma. The self-similar nature of lava flow surfaces make them difficult to draw.

Pyroclastic rocks are the fragmental products of explosive eruptions and their emplacement has similarities to that of sediments since they accumulate on the Earth's surface. The objective of sketches of volcanic rocks is often to record their stratigraphy in order to identify the events that occurred during eruption and the number of eruptive phases. Small-scale lithological features, such as the types and abundances of clasts, however, are also crucial in identifying the mechanisms of eruption and need to be recorded.

In this chapter, the important features to record in different occurrences of igneous rock are described together with tactics to record a sufficient level of detail to enable interpretation. Essential background information on igneous rocks and processes is also given

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to aid understanding of drawing techniques. The petrology of igneous rock types is described in Chapter 11 on hand specimens.

8.1 Intrusions

Intrusions of igneous rock range significantly in size from thin veins, which can be observed within hand specimens, to batholiths, which can extend across a landscape as far as the eye can see. Sketches of intrusions can, therefore, be on a wide range of scales depending on the type of intrusion.

8.1.1 Types of intrusion

Within individual outcrops, most intrusions of igneous rocks are broadly tabular in shape and are known generally as sheets. If sheet intrusions are parallel (concordant) to bedding of the older country rock they are known as sills, whilst those that cut across layering are known as dykes. The general term vein can be used for small sheet-like intrusions. Although sills and dykes are broadly separate, sills are often transgressive and step-up through bedding and thus have short segments that can be considered dykes. Although sheets are often observed as tabular intrusions on an outcrop scale they are usually lenticular on larger scales and close to a tip where they are propagating through new country rocks. Sheet intrusions also inflate as magma is intruded into them. In many outcrops of sheet intrusions the geometry of the intrusive body and nature of the contact with country rocks relate to the mechanisms of intrusion and are thus important to record in drawings.

The orientation of sheet-like intrusions often relates to their mode of emplacement along pre-existing weaknesses, such as bedding planes, joints or faults, but can also be controlled by regional tectonic stresses, producing swarms of parallel dykes where extension occurs. Dykes can furthermore occur in radial or concentric arrangements on where they are associated with doming or caldera collapse. Pre-existing structures within country rock, or those imposed by the intrusion of magma, are thus also important to include in diagrams.

Larger intrusions usually cannot be seen on an outcrop scale, although they may be observed across the landscape, if exposure is good. Shallow crustal intrusions are usually laccoliths, lopoliths, or pipes and are frequently sub-volcanic. Deeper in the crust intrusions

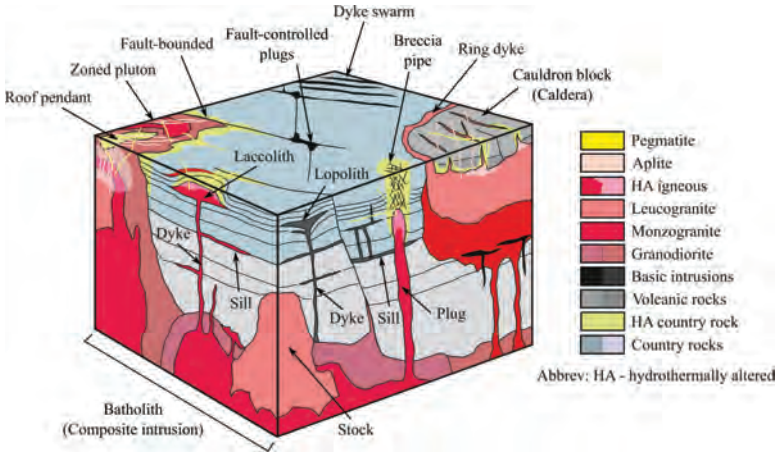

Figure 8.1 Types of intrusion.

include irregular cylindrical stocks several kilometres across and batholiths consisting of multiple composite intrusions tens to thousands of kilometres in size. The geometry of these larger intrusions will rarely be seen in the field, however, individual contacts can be observed. The geometry of contacts, presence of xenoliths and the nature of the country rock, such as contact metamorphism, are all important to record. The different types of intrusion are illustrated in Figure 8.1.

8.1.2 Drawing an intrusion

The example in Figure 8.2 shows a complicated set of intrusions from Yttre Ursholmen, an island in the Koster Archipelago on the west coast of Sweden. The interesting cross-cutting relationships in the outcrop would certainly be worth a field sketch. Here the contacts of the intrusions with the country rock are indicative of their mode of emplacement, and the intrusions cut across each other providing the relative timing of the intrusive events. The field relations also provide an excellent illustration of the generation of granitic magmas by crustal melting (anatexis).

Observation is always the first task in drawing; in fact it should come before the decision to draw the outcrop is made. In this case there are two obvious sheet-like intrusions, a prominent black intrusion in the centre of the image that cuts across a light-coloured, very coarse-grained intrusion containing some dark grey crystals. The dark

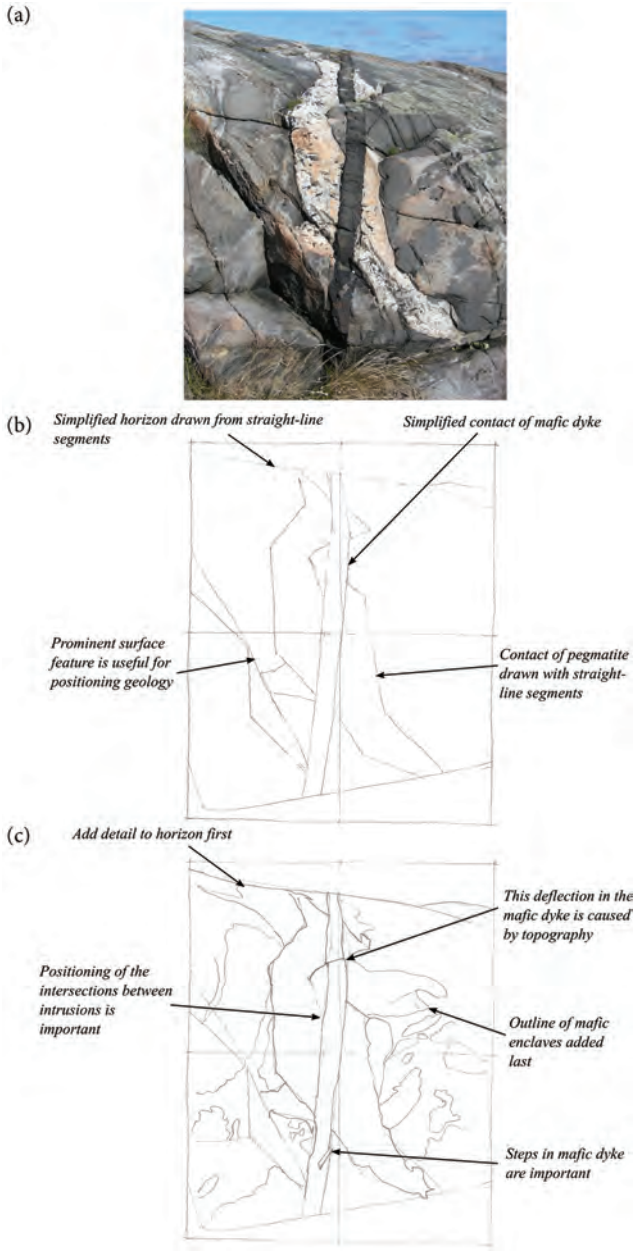
(a)
(b)
Simplified horizon drawn from straight-line segments
Simplified contact of mafic dyke
Prominent surface feature is useful for positioning geology
Contact of pegmatite drawn with straight-line segments
(c)
Add detail to horizon first
This deflection in the mafic dyke is caused by topography
Positioning of the intersections between intrusions is important
Outline of mafic enclaves added last
Steps in mafic dyke are important

Figure 8.2 Initial stages of drawing of cross-cutting relationships at Yttre Ursholmen island, Greenland (photo credit: Thomas Eliasson, Geol. Surv. Sweden).

intrusion is basalt—it is tabular in form with near parallel contacts. The light intrusion is a pegmatite and has a non-planar contact. The country rock is complex. On the right it contains grey irregular coarse-grained pods cut by nebulous light-coloured, felsic veins. These are migmatites—high-grade metamorphic rocks in which partial melting has occurred. On the right are darker grey gabbroic enclaves, formed by the intrusion of a mafic magma, surrounded by slightly pink granite. Some of the gabbroic areas form pillow-like objects owing to chilling of the mafic melt by the cooler granitic magma.

The subject of this sketch is the cross-cutting relationships and contact geometries of the various intrusions. Enough of the image has to be drawn to show the gabbroic enclaves, however, it is not necessary to draw them all. Once the area to draw has been selected, the sketch can be outlined with a rectangular grid to aid the placement of features. The most important lines to add first are the outline of the outcrop and horizon, and the margins of the two youngest intrusions. At first simple straight-line segments can be drawn to make it easier to ensure the geometry is accurate (Figure 8.2b).

Once the sketch has been blocked-in details can be added to the boundaries of the intrusions. Particularly important details are the deflection of contacts of the pegmatite across the basalt sheet. There are also some small angular steps and an angular crack-tip in the mafic sheet. The outlines of some of the near-by enclaves can also be drawn at this stage, as shown in Figure 8.2c.

A further level of relevant geological detail can now be added. There are mica crystals within the pegmatite that appear as radiating sheaths suggesting they grew by nucleation on the intrusion wall. Detail can also be added to the outlines of the gabbroic enclaves including slightly darker borders, which may be chilled margins (Figure 8.3a). The final drawing task is optional, there are some joints present, although these do not seem to have affected the boundaries of the intrusions and thus probably formed later. They can be added to the sketch, since they do have a minor interpretation.

Addition of descriptive and interpretive labels, a scale and a looking towards direction completes the sketch. Colour here is also useful since it emphasizes the differences in lithology, although some exaggeration is necessary. Including interpretative comments in the labels provides valuable context to this sketch. The deflection the pegmatite contacts across the mafic sheet suggest the latter opened mostly under regional extensional stress. The angular step and the crack-tip together are particularly

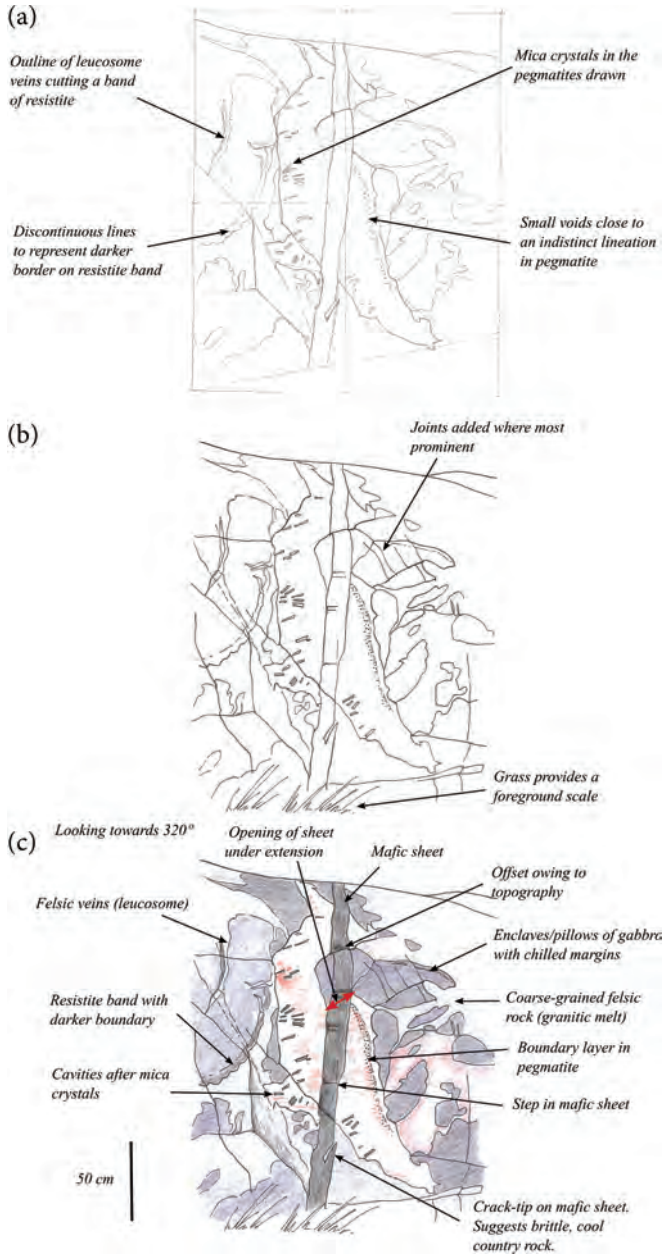
(a)
Outline of leucosome veins cutting a band of resistite
Mica crystals in the pegmatites drawn
Discontinuous lines to represent darker border on resistite band
Small voids close to an indistinct lineation in pegmatite
(b)
Joints added where most prominent
Grass provides a foreground scale
(c)
Looking towards 320°
Opening of sheet under extension
Mafic sheet
Offset owing to topography
Felsic veins (leucosome)
Enclaves/pillows of gabbro with chilled margins
Resistite band with darker boundary
Coarse-grained felsic rock (granitic melt)
Boundary layer in pegmatite
Cavities after mica crystals
Step in mafic sheet
50 cm
Crack-tip on mafic sheet. Suggests brittle, cool country rock.

Figure 8.3 Final stages of drawing of cross-cutting relationships at Yttre Ursholmen Island, Greenland.

significant since they indicate the country rocks were brittle, and thus cool, during intrusion of the mafic melt. This implies the mafic sheet was intruded much later than the formation of the migmatite and granite.

The migmatite is likely to have formed by heating and partial melting of lower crustal gneisses by gabbroic melt to generate the granitic magma—a process that is important in the genesis of granites in thickened crust worldwide. The brittle country rock thus also suggests sufficient time for denudation to decrease depth to the upper crust prior to the intrusion of the mafic sheet. In fact, here the mafic sheet intruded 280 Ma, whilst the gabbro and granite are 920 Ma in age. All this information cannot be included in labels, only those interpretations that directly relate to observed features. Field sketches, however, are always accompanied by field notes in which more detail can be given.

8.2 Lava flows

Lava flows extrude from central vents or fissures and produce sheets of magma that can extend for many kilometres. Drawings of lava flows from a distance are landscape sketches and can be used to record the number and identity of separate flow units. This can be difficult to achieve from aerial imagery alone, particularly when flows are old, weathered and partially vegetated. Outcrop-scale sketches of lava flows can be used to record their volcanological features, such as flow indicators, that can reveal the details of their emplacement.

The morphologies of lava flows vary considerably depending on the composition of the magma, temperature, degree of crystallization, vesicle content, extrusion rate, and external factors such as slope. Two general types of lava flow morphology are observed: (1) pahoehoe, which has a ropey texture on the surface formed by flow folds, and (2) Aa, which has an upper surface covered with brecciated lava. The term Aa is usually reserved for mafic lava flows, however, andesite and rhyolite lavas also have thick flow top breccias as well as levees of breccias that are similar to Aa, as shown in Figure 8.4. The distinction between pahoehoe and Aa is gradational—pahoehoe flow tops can become increasingly brecciated as they flow and cool.

There are several features of interest on the surface of lava flows. Hornitos are rootless cones where lava has erupted through the chilled flow top and are a form of breakout flow. Tumulus are large blister-like domes on the surface of flows underlain by large slugs of gas. Pressure

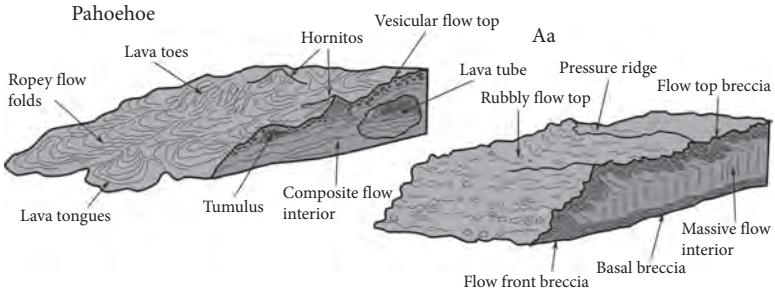

Figure 8.4 The morphology and terminology of lava flows.

ridges occur as elongate raised areas of flow top produced by compression during flow and are common on Aa, but can also occur on pahoehoe with rotation of blocks of flow top.

The internal structure of flows also varies. Pahoehoe often forms as composite flows consisting of many individual tongues that can weld back together within the flow. Lava tubes are often present and represent channels of magma flow below the surface that can sometimes intersect the surface. Where lava has partially exited the tube, they can form elongate caves. In thick flows, that have cooled slowly, the interior of the flow can be massive and contain columnar cooling joints. Finally, basal breccias are often present at the base of Aa flows and are often more welded than flow top breccias.

8.2.1 A sketch of pahoehoe

Sketches of the surfaces of recent lava flows can be particularly challenging because of the complex geometries of many of the features and the high level of detail required. The example in Figure 8.5 shows tongues of pahoehoe extruded from close to the summit of a sizeable hornito on a lava flow on Mount Etna. The image shows how successive tongues of pahoehoe have broken out of the hornito through brecciated earlier lava. The tongues form a raised platform and the direction of flow of some of the tongues is distorted by the topography of the earlier ones.

Drawing this structure first involves identifying the most important lines. Here the pahoehoe tongues form a conical platform on the side of the hornito. The outline of the platform is the most important feature to record. Once added to the sketch the boundaries of the individual

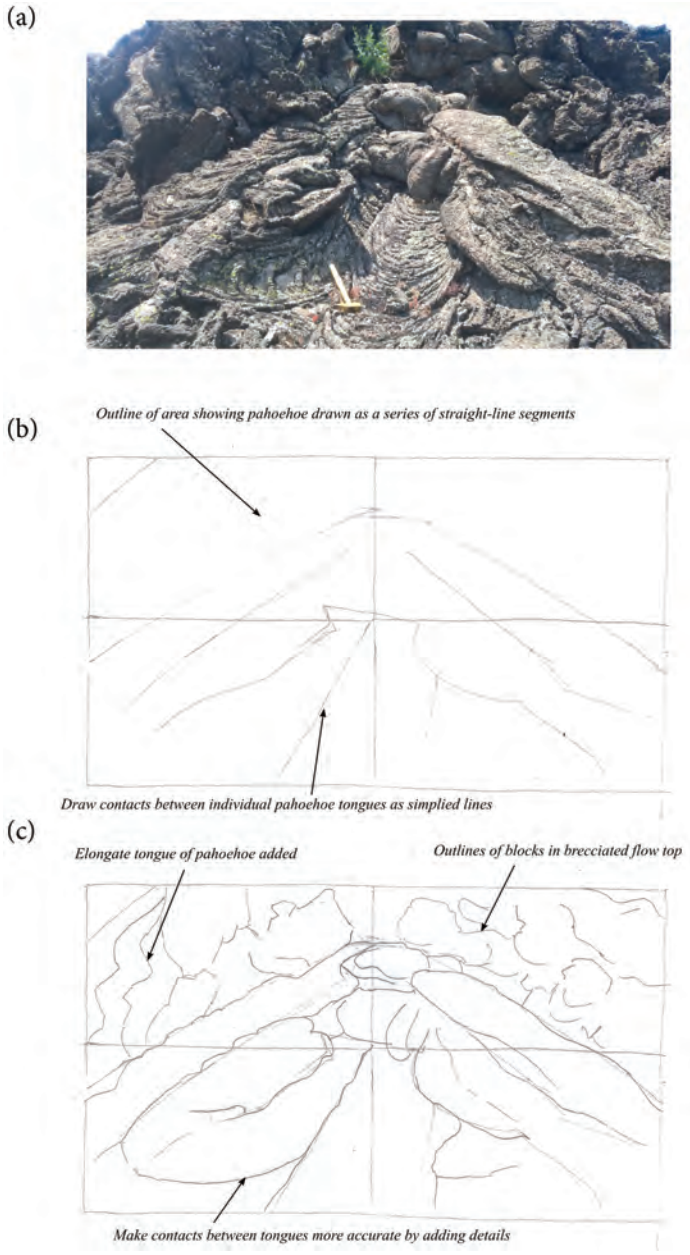
(a)
(b)
Outline of area showing pahoehoe drawn as a series of straight-line segments
Draw contacts between individual pahoehoe tongues as simplied lines
(c)
Elongate tongue of pahoehoe added
Outlines of blocks in brecciated flow top
Make contacts between tongues more accurate by adding details

Figure 8.5 Showing a sketch of pahoehoe on the 1651 lava flow near Bronte on Mount Etna.

tongues can be drawn as simplified lines to delimit separate areas of the sketch, as shown in Figure 8.5b.

The next stage of drawing is to amend the simplified boundaries of the pahoehoe to add details such as lobes and obvious folds. These features will be used to help position the numerous small flow folds of the ropey texture. The blocks of rubble at the top of the hornito can also be

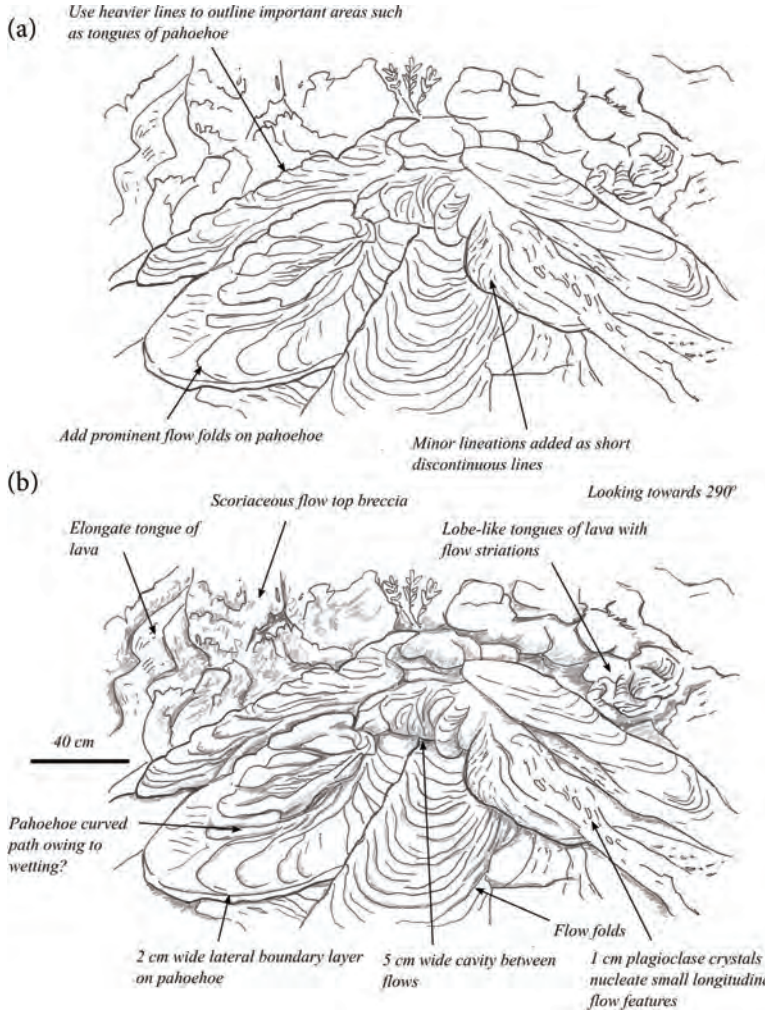
(a)
Use heavier lines to outline important areas such as tongues of pahoehoe
Add prominent flow folds on pahoehoe
Minor lineations added as short discontinuous lines
(b)
Looking towards 290°
Scoriaceous flow top breccia
Elongate tongue of lava
Lobe-like tongues of lava with flow striations
40 cm
Pahoehoe curved path owing to wetting?
Flow folds
2 cm wide lateral boundary layer on pahoehoe
5 cm wide cavity between flows
1 cm plagioclase crystals nucleate small longitudinal flow features

Figure 8.6 Showing the final stages of a sketch of pahoehoe.

drawn at this stage. The complex re-entrant shapes of these objects are difficult to draw accurately, however, since they merely provide content to the pahoehoe in front, a degree of simplification is acceptable and re-entrant lines can be used to draw them to emphasize their rubbly nature. A sinuous tongue of pahoehoe flowing through the rubble is also noted and added at this stage, as shown in Figure 8.5c.

The flow folds of the pahoehoe are perhaps the most important geological features to draw and can then be added. There are a great many folds and each one cannot be drawn so the most obvious are included. The shape of each fold is related to the adjacent ones and thus drawing them sequentially, from one end of a tongue to the other, greatly assists accurate representation. Several features are noticed whilst drawing the flow folds, such as a lateral boundary along the margins of some of the tongues of pahoehoe and lineations on the surface of some folds that relate to their inflation from within. These minor details can all be added to the sketch and increase its interpretative value, as shown in Figure 8.6a.

The final stage is to label, add scale, and looking towards direction. Colour is not particularly useful in this sketch owing to the near constant lithology; however, subtle shading can be added to enhance the three-dimensional nature of the tongues of pahoehoe. In bright sunshine, such as at this locality, directional shadows will be present and obscure detail. Ambient shadows that become darker in overhangs and crevasses provide a much better impression of volume. During inking-in thicker lines can be used to emphasize the shapes of the individual tongues of lava.

8.3 Summit craters

Stratovolcanoes often have summit pit craters formed by the excavation of rocks by the last significant explosive eruption. These craters can be hundreds of metres deep and occupy most of the summit area with only a thin crater rim from which they can be observed. Summit craters are often very difficult to record in detail since they occupy a significant proportion of the field of view and thus cannot be captured in a single photograph. Furthermore, the topography of summit craters often means they have deep shadows that obscure details in photographs. A sketch is thus a useful means of recording their most important features.

On mountain peaks, whether volcanoes or not, time is often limited, thus drawing is a strategic choice. Active volcanoes are particularly problematic since they pose a risk that is increased by exposure to the hazard. Often under such conditions quick sketches are made and can be supported by photographs that can be used to add detail later.

Often summit craters allow the volcanic products of the last few eruptive cycles to be examined. On the crater walls series of lavas interbedded with pyroclastic rocks are often exposed. Surrounding the pit, along the crater rim, are usually pyroclastic deposits, such as lapilli, scoria, or ash, derived from the last explosive activity. Preparation in the form of literature background is highly useful in observing and interpreting major units on volcanoes.

8.3.1 The summit crater of Vesuvius

The photograph in Figure 8.7 shows the summit pit crater of Vesuvius on the Bay of Naples in Italy. This volcano last erupted in 1944 and has been dormant ever since. Perhaps its most famous eruption is the Plinian event of AD 79 that destroyed the towns of Herculaneum and Pompeii. The sequence in the crater provides some insights into the recent evolution of this stratovolcano.

One of the challenges with such sketches is their initial proportions. This photograph is a panoramic that covers nearly 90° field of view. Drawing the crater involves turning the head, which always results in some difficulties in estimating the aspect ratio of the view. Begin by outlining the basic shape of the sketch. In this case the foreground represents the crater rim. The horizon can be drawn as simplified straight lines together with the most prominent bluffs that subdivide the sketch into regions of different scale.

The rough outline can be quickly improved by adding details. Care should be taken to position indentations and protrusions on the horizon since these will help when adding smaller-scale details. The scree at the base of the crater also can be drawn to delimit the entire height of the crater wall, as shown in Figure 8.7c.

The most geologically important boundaries and structures can now be added. There is clearly a red-brown pyroclastic breccia overlying a series of lavas exposed on the near rim of the crater. On the far side of the crater the breccia is covered by a grey lapilli-tuff with poorly defined bedding. These are the products of the 1944 eruption that initially generated a fire-fountain producing the welded pyroclastic breccia (splatter

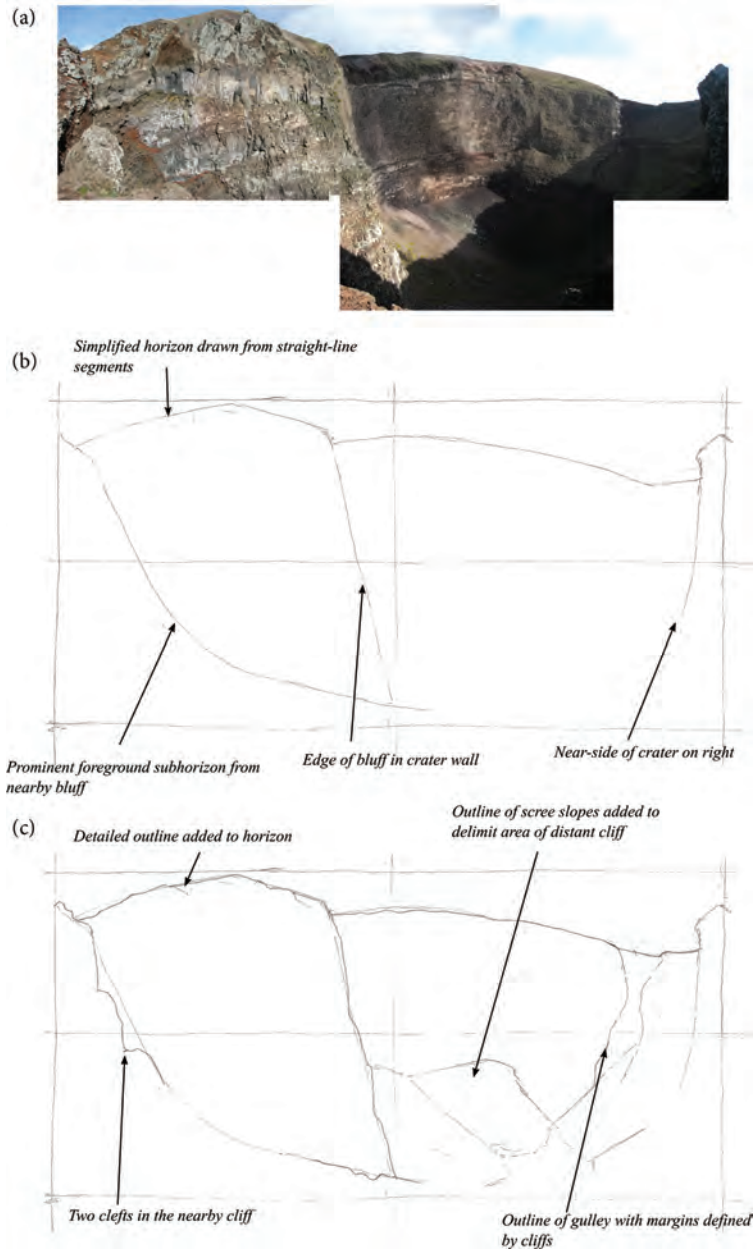
(a)
(b)
Simplified horizon drawn from straight-line segments
Prominent foreground subhorizon from nearby bluff
Edge of bluff in crater wall
Near-side of crater on right
(c)
Detailed outline added to horizon
Outline of scree slopes added to delimit area of distant cliff
Two clefts in the nearby cliff
Outline of gulley with margins defined by cliffs

Figure 8.7 The initial stages of a sketch of the crater of Mount Vesuvius.

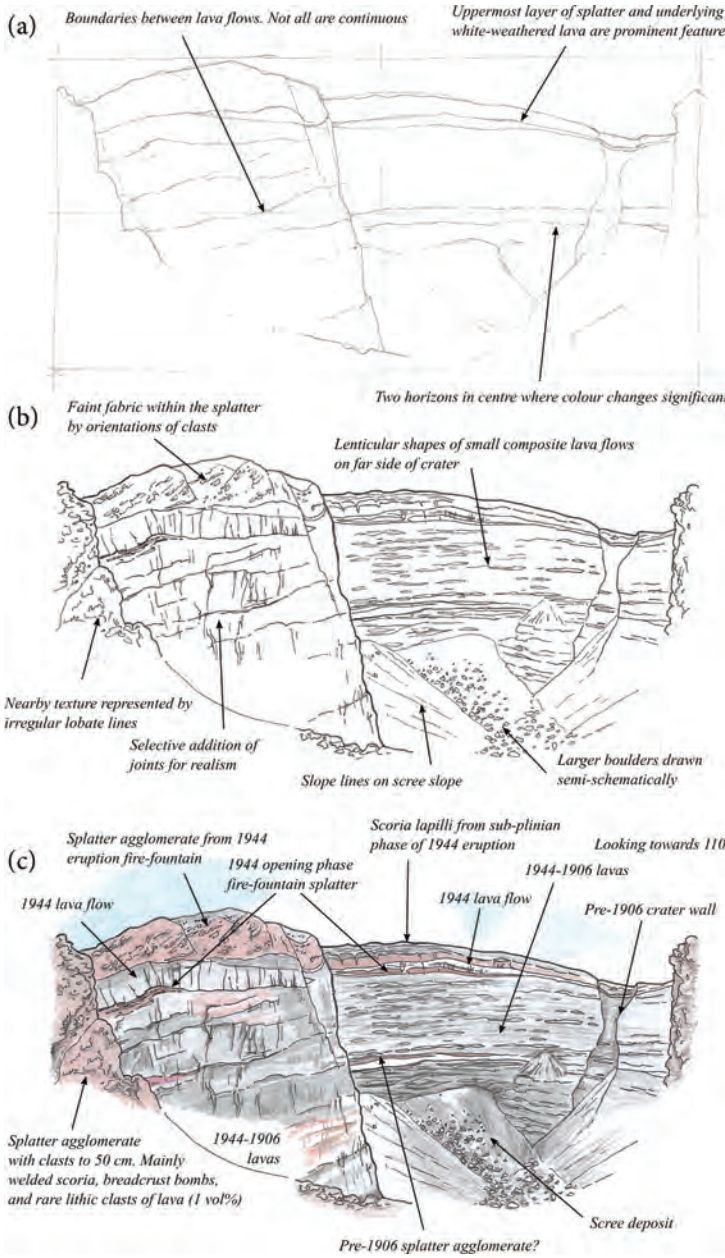
(a)
Boundaries between lava flows. Not all are continuous
Uppermost layer of splatter and underlying white-weathered lava are prominent features
Two horizons in centre where colour changes significantly
(b)
Faint fabric within the splatter by orientations of clasts
Lenticular shapes of small composite lava flows on far side of crater
Nearby texture represented by irregular lobate lines
Selective addition of joints for realism
Slope lines on scree slope
Larger boulders drawn semi-schematically
(c)
Splatter agglomerate from 1944 eruption fire-fountain
1944 opening phase fire-fountain splatter
Scoria lapilli from sub-plinian phase of 1944 eruption
Looking towards 110°
1944-1906 lavas
1944 lava flow
1944 lava flow
Pre-1906 crater wall
Splatter agglomerate with clasts to 50 cm. Mainly welded scoria, breadcrust bombs, and rare lithic clasts of lava (1 vol%)
1944-1906 lavas
Scree deposit
Pre-1906 splatter agglomerate?

Figure 8.8 The final stages of a sketch of the crater of Mount Vesuvius.

agglomerate) and then increased in energy to generate a sub-Plinian eruption column, which produced the grey lapilli. Underlying the splatter is a prominent lava flow on the crater wall that extruded in the months preceding the 1944 eruptions. An obvious change in colour also occurs at a dark horizon just below halfway down the crater wall. This probably marks the contact between the 1944–1906 lavas and the earlier lava flows. These important horizons can all be added to the sketch, as shown in Figure 8.8a.

Detailed elements can now be drawn to illustrate the sequence. There is a vague layering in the red brown pyroclastic breccia that can be seen dipping away from the crater on the left of the image. The scoriaceous surface texture of the breccia is obvious in the foreground.

Tracing the contacts between lava flows is difficult, since some of their colour variations appear to be due to weathering. On the far-side of the crater, in particular, the general bedding of the flows can be observed, but individual flow units are impossible to delimit and thus must be drawn semi-schematically as outlines of the most obvious white weathered flows. Several red-brown agglomerate layers can also be seen in the cliff. One is immediately below the uppermost lava flow and is discontinuous, suggesting there were some limited fire-fountains during the extrusive phase prior to the 1944 eruption. A similar red brown layer is present at the top of the pre-1906 lavas and may indicate that fire-fountains also began the activity after the explosive 1906 eruption. These details have all been added to Figure 8.8b.

The final task is to add descriptive and interpretive labels, scale and looking direction. Since there is a significant variation in lithology, colour is very useful to record. Some additional colouring can also be used to generate an impression of texture, for example, adding shadows to some joints and places where topography changes. Shadow can also be used to emphasize the rough surface of the splatter deposit.

8.4 Pyroclastic deposits

Explosive eruptions cause fragmentation of country rock and magma and result in the generation of fragmental volcanic products known as pyroclastic rocks. The term tephra is used for any fragmental product of explosive volcanism. These materials are broadly similar to clastic sedimentary rocks, since they consist of grains and clasts, and accumulate in layered sequences, albeit with different modes of emplacement.

The interpretation of pyroclastic deposits depends crucially on careful observations of their clast types and shapes, degree of sorting, stratigraphic relationships, and structures. Sketches of pyroclastic deposits provide a very useful means of recording these complex properties.

The lithological classification of pyroclastic rocks is relatively simple and based on clast size and relative abundance (sorting), as shown in Figure 8.9. Pyroclasts larger than 65 mm in size are termed blocks or bombs. Pyroclasts between 65 and 2 mm are termed lapilli, whilst the smallest grains are known as ash. The names used for pyroclastic rocks depend on the relative abundance of these different sizes of pyroclast. A lapillistone, for example, is a rock comprised mostly of lapilli, whilst a tuff consists mainly of ash, and a lapilli-tuff contains mostly lapilli and ash with relatively few blocks. These names are irrespective of the lithologies that make-up the component grains.

The lithology of pyroclasts is, however, very important in the interpretation of pyroclastic deposits and needs to be recorded in the field. Juvenile pyroclasts are those derived from fragmentation of magma and can include bombs such as breadcrust, cowpie, or spindle bombs. The majority of juvenile pyroclasts are highly vesicular pumice (or scoria if mafic), and glass shards in the ash size fraction. Crystals are also a common component in the ash. Most other pyroclasts are lithic clasts formed by the fragmentation of pre-existing rocks, which are often also

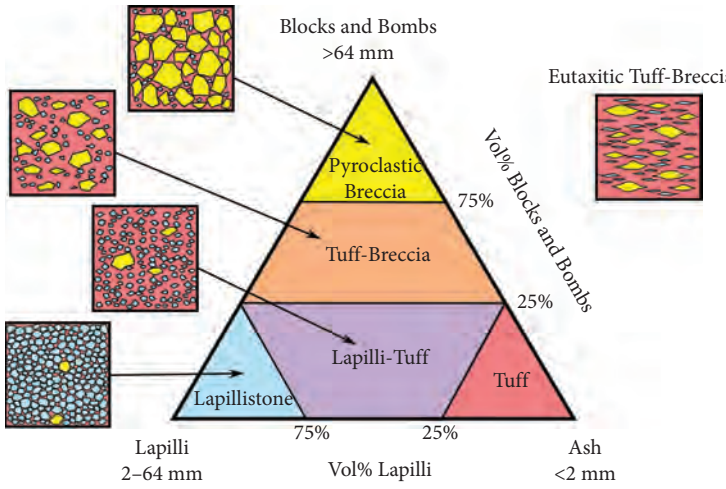

Figure 8.9 The classification of pyroclastic rocks.

volcanic rocks. It is useful to draw pyroclasts in the field to record their lithologies.

Pyroclastic rocks can be emplaced as ballistic ejecta, as airfall, or from ground-hugging flows, as illustrated in Figure 8.10. Ballistic ejecta tend to accumulate in the proximity of a vent and typically forms lapillistones and pyroclastic breccias. Often these are hot when emplaced and weld to form splatter agglomerates—typical products of fire-fountains from Hawaiian activity, or bombs generated by Strombolian activity. Airfall is generated by pyroclasts settling out under gravity from an eruption column developed over the vent. Airfall is typically poorly sorted forming lapilli-tuffs or tuff-breccias, however, it becomes finer-grained with distance from the vent where it is dominated by ash. Airfall can be stratified owing to fluctuations in flow in the column or vent and can have lithic-rich layers representing collapse of the vent walls during an eruption. Each layer in airfall, therefore, need not represent a separate eruption. Reverse-grading in airfall is common and associated with unsteady eruption columns that increase in energy, for example, owing to erosion of the vent walls. Airfall can contain ballistically emplaced bombs which deform layering to produce bomb sags.

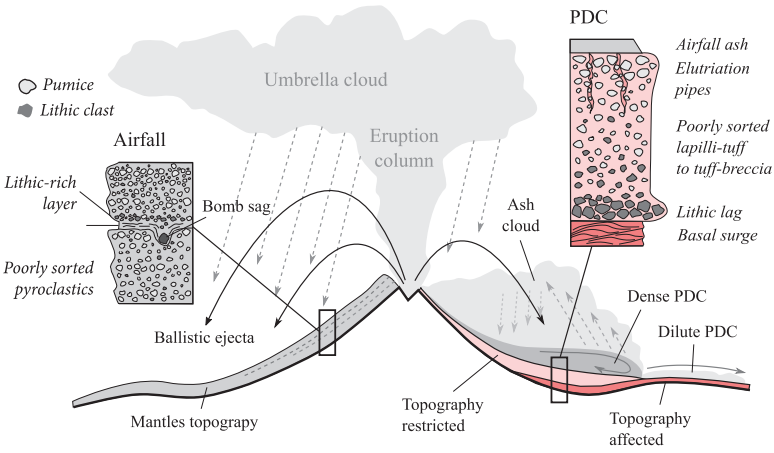

Figure 8.10 Illustrating idealized airfall and flow deposits. The airfall shows an example of a vent blockage causing fallout of an ash layer followed by a lithic-rich layer produced during clearing of the vent. The deposits of pyroclastic density currents are highly variable and can lack one or more of the features shown.

Pyroclastic deposits emplaced by flows are more complex than airfall or ballistic ejecta. Flows formed during explosive eruptions are slurries of solid clasts and grains suspended in gas. These used to be termed pyroclastic flows if they were dense flows, dominated by solid fragments, or surges if they were dilute flows, dominated by gas. Recently these have been grouped together and termed pyroclastic density currents (PDCs). Typically, dense PDCs form poorly sorted deposits of lapilli-tuff or tuff-breccia. They can also have basal lithic breccias, formed by settling of dense clasts to form lags, and overlying ash layers, formed by ash clouds generated by removal of fine-grained material from the flow. Some dense PDCs can also be graded with dense lithic clasts concentrated near the base of the flow and large, low density, pumice concentrated towards the top. Examples of PDC deposits were shown in Section 7.1 in a landscape sketch of a volcanic crater.

Pumice-dominated pyroclastic flows are termed ignimbrites and are usually emplaced at significant temperature. Evidence for emplacement at elevated temperature can be seen in the presence of fossil fumaroles or elutriation pipes formed by the escape of gas and fluid, and the presence of charcoal derived from ingested plant matter. In high temperature flows pumice clasts can weld and flatten to produce eye-shaped glassy structures known as fiamme, generating a eutaxitic texture. Such deposits can often have red or pink groundmasses of welded glassy shards in which the colour is generated by rapid oxidation of iron, promoted by their high temperature. In the highest temperature, high grade ignimbrites, pumice and glass shards can entirely weld together to generate melt. Such deposits can be sufficiently fluid to flow downslope after emplacement generating rheomorphic flow structures.

Dilute PDCs are typically ash, lapillistones, or lapilli-tuffs and are often cross-laminated with low angle dune structures. Some dilute PDCs can be associated with dense flows, often as a basal layer formed by ejection of ingested air. Lithic-dominated dilute flows are often base surges associated with explosions, for example, those generated by interaction between magma and water.

Identifying the mode of emplacement of pyroclastic deposits is difficult and involves interpretation of a wide range of lithological and stratigraphical observations. Airfall and ballistic deposits, for example, tend to shroud topography with little variation in thickness, whilst dense PDCs are often restricted to topographic lows, whilst dilute PDCs are thicker in topographic lows than on topographic highs. Pyroclastic

deposits may also be fluvially reworked or remobilized in landslides. As a result of the difficulties in interpreting deposits it is best to avoid using interpretative terms such as airfall or PDC deposit in descriptions of pyroclastic deposits and instead use lithological terms such as pumice lapillistone or lithic-rich lapilli-tuff. Drawings of pyroclastic deposits need to record their stratigraphy, structures and lithology in order to allow interpretation of their emplacement mechanisms.

8.4.1 Sketch of pyroclastic deposits from Santorini

Pyroclastic deposits from the Lower Tuff sequence of Santorini are shown in Figure 8.11 and illustrate the typical complexity of pyroclastic deposits. The lithological variation between layers in this photograph can be seen by their colour, relating to composition, clast type, and grain size. Structures are also present that provide evidence for mode of emplacement. Exposures with such diverse properties are best recorded with sketches.

Observation of the exposure should be performed first to evaluate the most important features to be drawn and the area of the exposure to be recorded. The most obvious unit is the light-grey lapillistone that makes up most of the upper half of the field of view. It has a constant thickness and exhibits no significant variation in grain size and is probably a Plinian airfall deposit. Penetrating the upper surface of the lapillistone is a 40 cm wide black clast that is likely to be a bomb, as suggested by its indentation of the upper contact of the lapillistone, forming a bomb-sag. Overlying the pumice lapillistone is a pyroclastic breccia with large clasts of dark-coloured andesite in a finer-grained matrix containing pumice. This could be a lag on a PDC deposit. At the bottom of the exposure is an ochre lapilli-tuff dominated by pumice but with some lithic clasts. Its origin is unclear, however, it has a fine-grained upper surface containing angular clasts that may be a palaeosol. Finally, between the light-grey lapillistone and the ochre lapilli-tuff is packet of interbedded deposits that include ash layers and lapillistone that vary in colour from grey to ochre.

Once the general sequence has been evaluated the sketch can be blocked-in by adding the most important lines to the notebook. The contacts between the different lithologies and the base of the exposure are the most important boundaries to be added at this stage. The bomb and the lenticular area of finer-grained, laminated pyroclastic rock that infills the sag can also be drawn, as shown in Figure 8.11b.

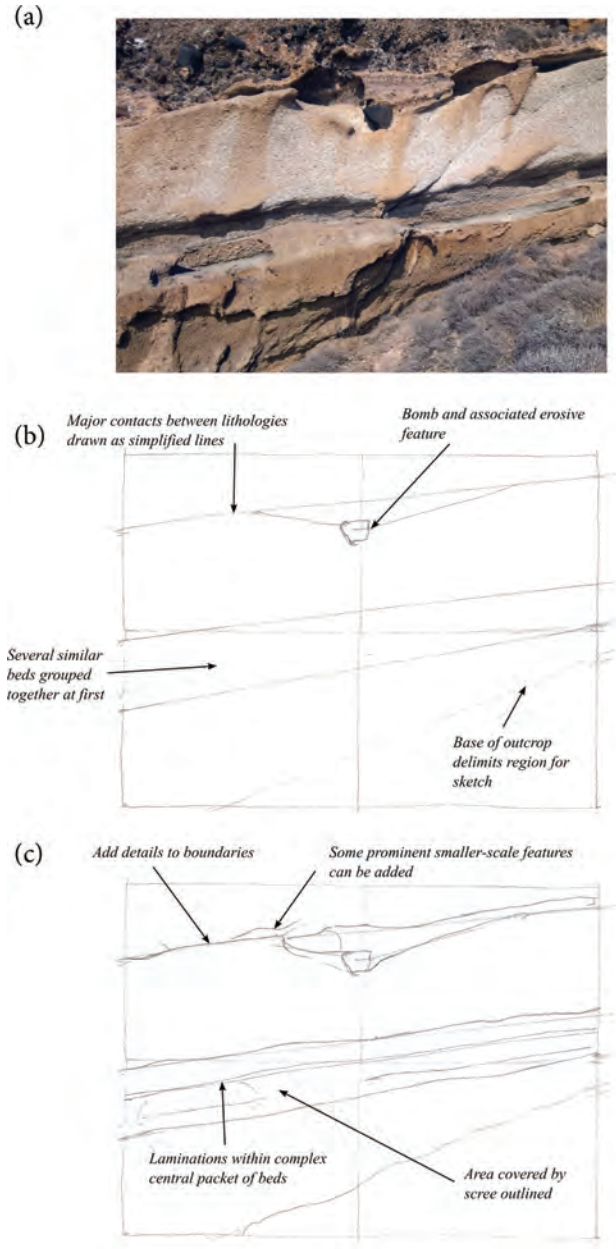
(a)
(b)
Major contacts between lithologies drawn as simplified lines
Bomb and associated erosive feature
Several similar beds grouped together at first
Base of outcrop delimits region for sketch
(c)
Add details to boundaries
Some prominent smaller-scale features can be added
Laminations within complex central packet of beds
Area covered by scree outlined

Figure 8.11 The initial stages of a sketch of the Lower Pumice sequence of Santorini.

The simplified lines drawn to denote the major boundaries can now be amended to record protrusions and deflections on these surfaces. The bomb sag, for example, curves downwards on the left and meets the outline of the bomb at its upper surface, whilst on the right the sag rises in a convex upwards curve from the base of the bomb. Additional important details can also be added at this stage. There are several prominent contacts between lithologies in the central packet of beds that are relatively easy to see and can be recorded. There are a couple of areas on the left-side of the image where a small amount of scree obscures this packet of beds. These areas of no exposure can also be drawn, as shown in Figure 8.11c.

The sketch now records much of the important spatial information, however, lithological data is crucial in the interpretation of pyroclastic deposits and such detail needs to be included. In the lithic pyroclastic breccia at the top of the exposure, some of the clasts are large enough to be drawn accurately, however, in the rest of the units only a small proportion can be drawn and they have to be exaggerated in size slightly for them to be visible. Particularly important is clast shape. Some of the detail in the central packet of beds can also be drawn, particularly the poorly developed low angle cross-laminations since these imply emplacement by a dilute PDC.

Some ancillary features can also be included in the sketch. Vegetation is always useful to record since it provides a visual foreground scale and takes only seconds to draw. Joints present in the light-grey pumice lapillistone may be have some significance, since they are parallel and dip down-slope. They may represent slumping of the airfall on the slope. Finally, in the basal ochre lapilli-tuff there are raised protrusions on the surface that might represent fumaroles rising through the deposit and causing limited mineralization. These additional features have been added in Figure 8.12b.

Finally, the sketch should be labelled, and a scale and looking toward direction added. Care should be taken to avoid mixing descriptive and interpretative labels, although both are perfectly permissible. Some degree of interpretation of sketches is always advisable. Colour is also particularly useful in this sketch to highlight and record the different lithologies that are present. Shading is optional but has some value in showing the different responses to erosion.

Peripheral sketches showing an area of an exposure at higher resolution can be useful when there are regions with significant lithological variation over small distances. The decision whether to draw such

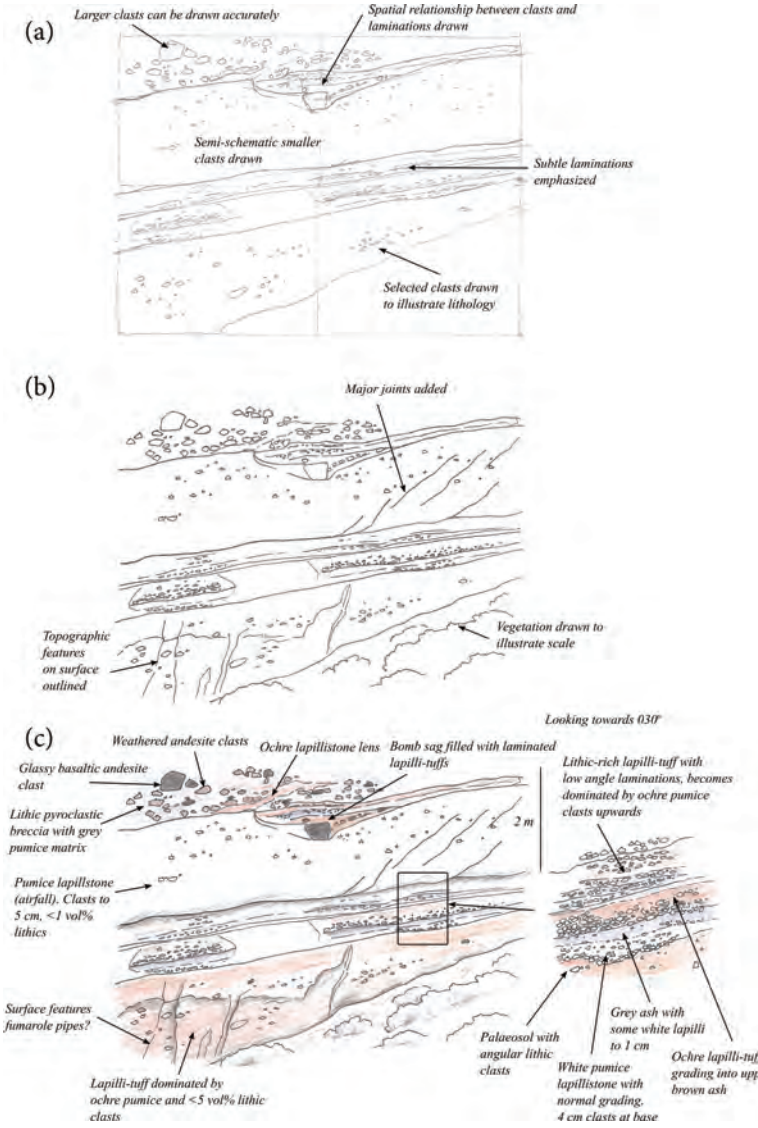
(a)
Larger clasts can be drawn accurately
Spatial relationship between clasts and laminations drawn
Semi-schematic smaller clasts drawn
Subtle laminations emphasized
Selected clasts drawn to illustrate lithology
(b)
Major joints added
Topographic features on surface outlined
Vegetation drawn to illustrate scale
(c)
Looking towards 030°
Weathered andesite clasts
Ochre lapillistone lens
Bomb sag filled with laminated lapilli-tuffs
Glassy basaltic andesite clast
Lithic pyroclastic breccia with grey pumice matrix
Lithic-rich lapilli-tuff with low angle laminations, becomes dominated by ochre pumice clasts upwards
2 m
Pumice lapillstone (airfall). Clasts to 5 cm, <1 vol% lithics
Surface features fumarole pipes?
Palaeosol with angular lithic clasts
Grey ash with some white lapilli to 1 cm
White pumice lapillistone with normal grading, 4 cm clasts at base
Ochre lapilli-tuff grading into upper brown ash
Lapilli-tuff dominated by ochre pumice and <5 vol% lithic clasts

Figure 8.12 The final stages of a sketch of the Lower Pumice sequence of Santorini.

diagrams in the field depends on the time available and on the additional value they provide. Peripheral sketches are particularly useful in drawings of pyroclastic deposits, sedimentary sequences, and complex structures in metamorphic rocks. A peripheral sketch has been included in Figure 8.12c to show the lithological variation in the central packet of beds. These diagrams need not be drawn adjacent to the main sketch and can be included on subsequent pages and linked to the main sketch by titles such as 'Area A', 'Area B'.

8.5 Common mistakes

8.5.1 Imprecise line style

Perhaps the most common mistake made by those who are artistic is to use imprecise scratchy line styles, as shown in Figure 8.13. Drawing lines

Figure 8.13 Illustrating a sketch made with imprecise line style.

by quick back and forth motions with a pencil is a common technique in sketching in art but leads to inaccuracy in the placement and shape of lines. Precise simple lines are preferred in scientific diagrams.

8.6 Key concepts

In this chapter, several key concepts and methods were introduced:

- Recording the nature of contacts is particularly important in drawing igneous outcrops, in particular cross-cutting relationships that relate to emplacement timing.
- Blocking-in accurately is most important for those exposures with high densities of small-scale features such as upper surfaces of lava flows.
- In pyroclastic sequences lithological information such as clast sizes and shapes are important to record. A subjective choice must be taken on how many and which clasts are drawn.
- Peripheral higher resolution diagrams are very useful in drawing igneous rocks where important spatial evidence exists on very different scales.

9

Drawing sedimentary outcrops

Sedimentary rocks are perhaps the most abundant group of rocks on the land surface of the Earth and provide a record of the past environment, geography, and history of our planet. It is through the study of sedimentary rocks that we understand much of the history of life, gleaned from the fossils contained within these strata. Every geologist, whatever their specialization, must study sedimentary rocks and processes since they are so prevalent. Interpreting sedimentary rocks involves detailed observation of their lithologies, sedimentary structures, stratigraphic relationships and fossil assemblages and thus involves combining features very different in scale. The complexity of outcrops of sedimentary rocks means field sketches are highly useful in recording their properties.

In this chapter, an approach to drawing sedimentary rocks is described that focuses on recording their surfaces in order of importance. Bedding is the most crucial feature to begin recording and establishes the geometric elements of an outcrop by which sedimentary structures, erosional features, and clasts can be drawn. Sedimentary rocks have such diverse lithologies, structures, and stratigraphy that an appreciation of the significance of their components is necessary in deciding which are the most important features to draw. This chapter will begin, therefore, by describing the fundamental concepts of sedimentary stratigraphy, structures, and the types of evidence used to deduce depositional environment. The lithologies of sedimentary rocks are described in Chapter 11 on hand specimens.

9.1 Sedimentary rocks and stratigraphy

Beds are the fundamental unit of sedimentary rocks and represent layers of different sediment grain size, colour, mineralogy, or composition. This stratification occurs on scales from less than a millimetre to many tens of metres. However, beds are considered to be those layers thicker than 1 cm, whilst thinner layers are termed laminations. Beds

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are fundamentally important since they are the smallest unit in lithostratigraphy—the subdivision of sedimentary sequences on the basis of the lithologies of rocks. At the scale of a single outcrop, the stratigraphy of sedimentary rocks is mostly considered in terms of the variation in lithology. Bedding is thus the most important feature to draw in any sketch of sediments.

Most beds are parallel tabular bodies of rock at the outcrop scale; however, they can vary in thickness along length over short distances and be wavy or lens-shaped. Beds are separated by bedding planes at which a discontinuous change in lithology occurs, for example, a change in grain size. Very rarely is bedding not observed within sedimentary rocks in the field, and usually only in those units where beds are very thick, such as in reef limestones or thick accumulations of conglomerate or mudstone.

Distinguishing bedding from other planes within a sedimentary rock, such as joints, faults, and cleavage, is usually the first task at a sedimentary outcrop. Usually bedding planes are the most obvious surfaces in an exposure; however, sometimes jointing can be prominent and make bedding more challenging to observe. Bedding can be identified since it is marked by a change in lithology. Planar laminations can also be used to help locate the bedding orientation, in particular where rocks are thickly bedded, since laminations are sub-parallel to the bedding plane. Even where jointing is the more prominent plane, bedding is emphasized in drawings of sediments.

Interbedded units, where beds alternate between two different rock types, such as sandstone and mudstone, are common in sedimentary sequences. In lithostratigraphy beds of different lithology are grouped together into named formations. Each formation is lithologically distinct from other formations in the sequence and should be of sufficient lateral extent that they are useful in the mapping of an area. Formations, however, can have gradational boundaries with each other. A formation of interbedded limestone and mudstone beds, for example, may grade into a formation comprising interbedded sandstones and mudstone beds, by the gradual appearance of sandstone and the disappearance of limestone. Formations are typically tens to hundreds of metres thick but can be sub-divided into smaller units called members, which comprise one or more beds that are sufficiently characteristic. Formations can also be combined into groups if they are related, for example, by deposition in the same basin. The variable lithology of beds within

formations is crucial to record in sketches since it relates to the environment in which they were deposited.

Even though formations can consist of beds of different types of rock, these all form by deposition within a broadly similar environment, for example, in a field of sand-dunes, or within the centre of a lagoon. Formations do not, however, represent deposition at the same time and tend to vary in age laterally. This variation in age occurs as the depositional environment migrates as a result of changes in sea level or basin subsidence. Formations are thus diachronous (varying in age) but represent deposition of a characteristic set of lithologies under similar conditions in the same sedimentary environment. A sedimentary sequence thus represents a stack of formations formed in different sedimentary environments that were arranged adjacent to each other at a single moment of time—a concept known as Walther's law. Often the objective of field studies of sedimentary rocks is to identify the nature of the depositional environment and how it changes with time. The concept of formations and groups and their relationship to sedimentary environment is illustrated in Figure 9.1.

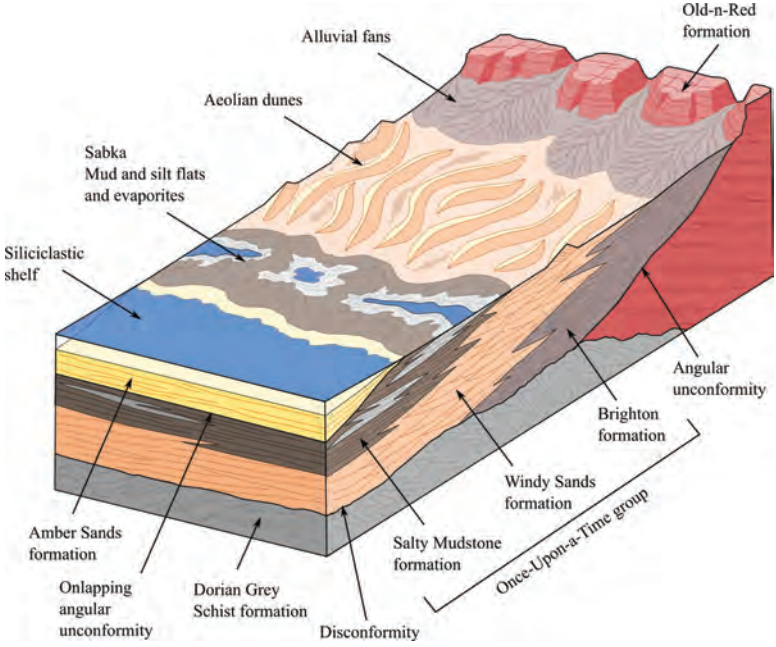

Figure 9.1 Illustrating concepts in litho- and sequence stratigraphy.

Within formations beds can provide information on small-scale changes within an environment. The width and frequency of beds can reflect the rate of sediment supply and may change as a result of climatic conditions or proximity to source. Storm-related influxes of sand onto a marine shelf dominated by mud, for example, could produce interbedded sandstones and mudstones. Thickening of sandstone beds upwards might indicate shallowing water and proximity to the source of the sediment. An increase in the frequency of sandstone beds, in contrast, could relate to an increased occurrence of storm events and thus a climatic control. Often these changes in bed width, frequency, and/or thickness prove to be cyclic and each cycle may also increase or decrease in width upwards, revealing longer term climate cycles. Observations of bed thickness, frequency, and grain-size changes across outcrops and between outcrops thus can have significant implications and are important to record in drawings.

Unconformities are particularly important surfaces that truncate sedimentary sequences and often mark sub-aerial exposure and erosion. They represent discontinuities within the depositional history of a sedimentary sequence that separate periods of near continuous sedimentation. Unconformities are usually worth drawing in the field since their features often reveal the events that lead to the break in deposition. The truncation of sedimentary sequences by unconformable surfaces breaks the link between two formations with the result that their depositional environments were not necessarily geographically adjacent.

The most obvious unconformities occur where sediments are deposited onto igneous or metamorphic basement that has experienced long-term erosion. These surfaces usually form the base of sedimentary basins and are known as nonconformities. They represent significant breaks in deposition often separated by deformation and metamorphism of rocks and lengthy periods of erosion.

Angular unconformities often also represent significant breaks in deposition with deformation and erosion occurring over an extended period. These unconformities are defined by the different dip of beds above and below the unconformable surface, indicating tilting and erosion of the underlying strata. Overlying sediments may onlap over an unconformity becoming progressively younger in one direction as wedge-shaped bodies. The opposite arrangement is known as offlap. Often conglomerates overlie angular unconformities and contain clasts

derived by erosion from the underlying strata. Angular unconformities can have planar surfaces or can mantle topography.

Where significant angular mismatch is absent between underlying and overlying sediment, unconformities are known as disconformities and represent minor periods when erosion or non-deposition has occurred. Disconformities are often marked by palaeosols, karsts, or hardgrounds formed by exposure of the surface for a period of time. Disconformities often pass laterally, on scales larger than a single outcrop, into surfaces that have no discernible break in deposition (i.e. are conformable). Where a hiatus (time break) in deposition can only be identified from the age of sediments, for example from their fossil assemblages, the surface is known as a paraunconformity.

9.1.1 Sedimentary structures

Often an important objective of studies of sedimentary rocks is to identify the environment in which the sediments were deposited. Structures within sedimentary rocks provide important evidence for depositional environment and are thus usually important to record in the field. Those structures that testify to the operation of currents are often the most useful. Typically, the geometry of sedimentary structures is crucial in their interpretation and thus accurate drawings of them are important.

The commonest current-related sedimentary structures are cross-stratifications where underlying laminated sediments are truncated by overlying layers. Where truncations occur at scales of <6 cm these are generally known as cross-lamination and form as a result of the migration of surface ripples. Where truncations occur at larger scales they form cross-bedding and are generated by the migration of dunes. Both ripples and dunes are created by currents transporting sediment in water or in air. The laminations that make up cross-stratification form by transport of grains up the less-steep, stoss side of the structures followed by deposition on the steep leeside, as shown in Figure 9.2. The layers generated by the deposition of grains on the leeside slope are known as the foresets and combine to make a set of laminations deposited by a single ripple or dune.

The migration of dunes or ripples causes them to cut through the deposits left by the previous structure, usually removing the upper portions and stoss-side laminations to produce cross-stratification that consists mainly of foresets. When sediment is abundant, however, climbing ripples form that can that preserve the stoss-side laminations.

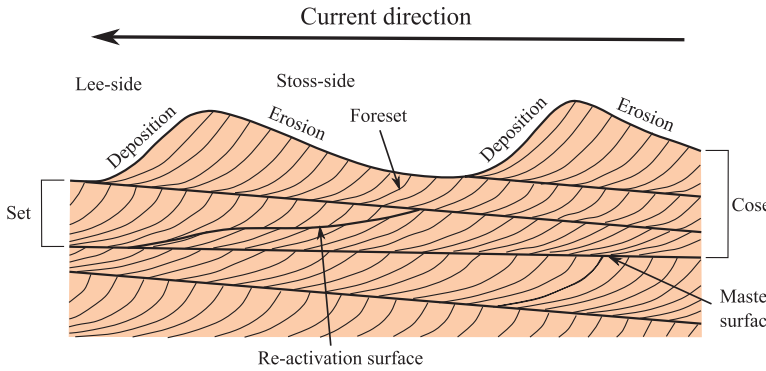

Figure 9.2 The formation of ripples and dunes showing their internal cross-stratification.

Related foreset beds, formed by the same generation of dune, form a packet known as a coset.

Dunes stop migrating during periods when current is insufficient to transport grains. This may occur at high and low tide in an estuary, or during seasons with little wind in areas with sand dunes. Erosion during such periods creates truncations known as reactivation surfaces. Larger discontinuities in current, for example, when a new river channel cuts across deposits from an older channel, generates near bedding-parallel master surfaces between different cosets of dune (Figure 9.2). There are, therefore, many important surfaces to draw in cross-stratified sedimentary rocks and a careful inspection of the geometry of laminations is necessary.

There are many different morphological types of cross-bedding. The two commonest are tabular and trough cross-stratifications. Tabular cross-stratifications are formed by straight-crested ripples or dunes and have linear truncations when viewed on the bedding plane, although in section their forests can be planar or curved at the bottom of the foreset. Trough cross-bedding forms from arcuate dunes and exhibits cross-cutting curved laminations on the bedding plane. The foreset surface formed by the laminations is trough-shaped and elongate in the current direction.

Common cross-stratification types are shown in Figure 9.3. Tabular and trough-cross bedding are common in a wide range of environments since ripples and dunes occur in rivers, deserts and in shallow marine environments. Some structures are, however, more characteristic. Hummocky cross-stratification, for example, is formed by currents

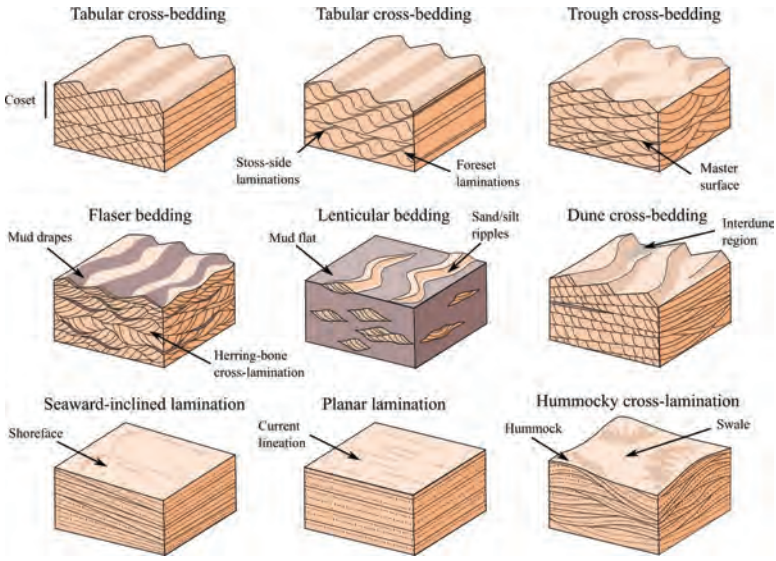

Figure 9.3 Types of cross-stratification.

generated by storm waves on marine shelves. These indicate water depths too deep to be affected by smaller fair-weather waves but shallow enough that storm waves generate currents (i.e. between the fair-weather and storm wave base). Wave-formed ripples in general tend to have complex internal laminations with many truncations and laminations that are not parallel to the profile of the ripple. Often, they have symmetrical profiles but can be asymmetric or have flat crests. These structures arise due to the complicated nature of the currents generated by waves.

Cross-stratification formed by tidal currents are often bidirectional and feature herring-bone cross-lamination, where foresets dip in opposing direction in adjacent sets representing the reversal of current by tides. Many tidal cross-stratified deposits, however, are unidirectional, since one direction of the tidal current is stronger than the other. Features such as drapes of mud to form flaser bedding are, however, common within tidal deposits, although they are not restricted to these environments. Where mud dominates, isolated sand or silt ripples can appear to produce lenticular bedding which is particularly common on tidal flats and in delta fronts.

Other cross-bedding types can also be characteristic. Large aeolian dunes often result in high angle planar cross-beds with foresets larger

than 1 m. These are larger than dunes found in most fluvial or marine settings. Low angle planar cross-lamination is also significant and tends to be associated with beach shore faces.

Even planar laminated sediments have significance. Those consisting of compositional layering, for example, mud and silt, tend to form by settling of sediment out of suspension in low current environments. Planar lamination in sandstones, however, can form due to high velocity planar flow and often have a current lineation on bedding planes. These can form in numerous environments including within rivers but are particularly common in marine debris flows known as turbidites.

In addition to appearing as internal stratification, sedimentary structures also occur on the bedding surface. Ripple marks are common in siltstones and sandstones and can be bifurcating, straight-crested, sinuous, linguoid, or lunate in shape with increasing current velocity. The interpretation of ripple marks is, however, difficult without inspection of internal lamination. Other current related bed forms include flute, groove, and tool marks on the base of beds formed by scouring by currents or clasts. Some structures on bedding surfaces are formed by processes other than currents such as mud-cracks produced by desiccation during sub-aerial drying and rain-prints produced by impact of rain droplets on a mud or silt surface. Other bedding plane structures are the result of biological action and are ichnofossils. These are described in Chapter 10. Bedding plane structures are often worth drawing but can also be recorded adequately with photographs.

Sedimentary structures are diverse and of great use in the interpretation of depositional environment. They are also wide-spread occurring in any clastic sediment irrespective of whether these consist of siliciclastic or carbonate grains. Often, they require detailed observation of the cross-cutting relationships and shapes of laminations, or their three-dimensional nature on a bedding surface. Recording sedimentary structures is thus often achieved by drawing them at the outcrop where such details can be observed at sufficient resolution. A great many more sedimentary structures exist than can be described here and more details can be found in textbooks on sedimentary rocks such as *Sedimentary Rocks in the Field* by Maurice Tucker.

9.1.2 Facies and depositional environment

Although some sedimentary structures can be considered characteristic of certain depositional environments they often are not exclusive to

them and thus cannot be used to uniquely identify the environment in which the sediments were deposited. The interpretation of depositional environment usually requires a combination of diverse features including the lithologies, sedimentary structures, and fossil assemblages. These features in combination are termed the sedimentary facies.

Commonly encountered sedimentary facies are shown in Figure 9.4 in the form of idealized logs (see Section 9.5), which illustrates how numerous features must be considered together in order to evaluate

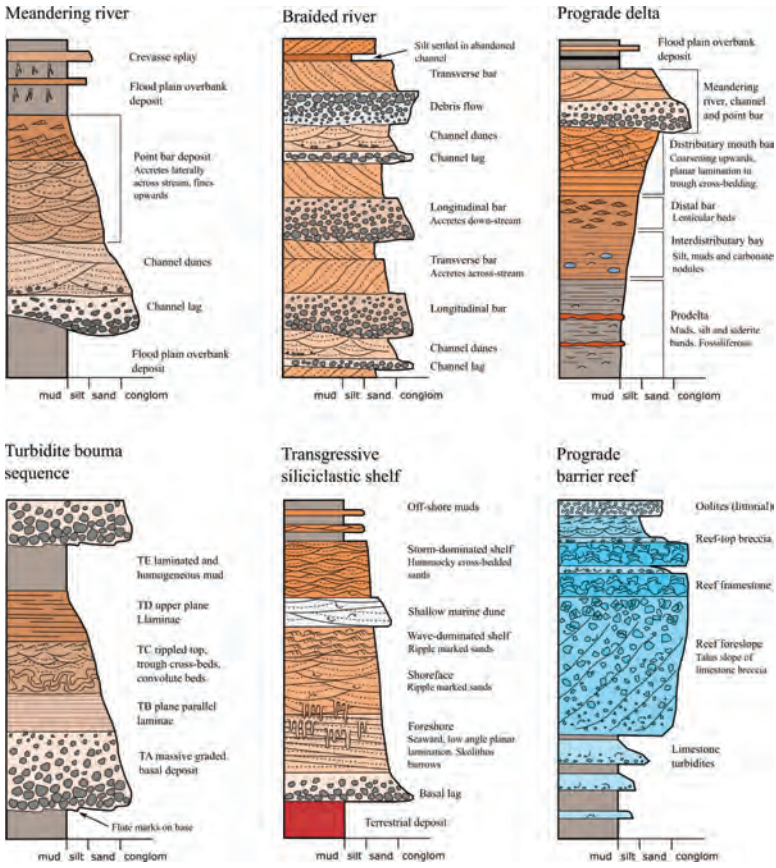

Figure 9.4 Commonly encountered sedimentary facies shown as schematic logs. The change in the lithology is shown by the width of the column, which represents grain-size. Sedimentary structures are drawn on each layer. Colours are used to distinguish units with different origins.

depositional environment. The facies exhibited within a formation will usually be related to adjacent formations as a result of the migration of sedimentary environments.

Interpretation of depositional environment involves facies analysis and the collection of varied data on numerous scales that is likely not to be achieved at a single exposure but through observations at multiple localities. Field sketches of sedimentary rocks assist greatly in the interpretation of facies since drawings make data easier to review and analyse than written descriptions. Schematic diagrams showing the relationships between facies (Figure 9.1) are also a valuable tool in conceptualizing past environments.

9.2 Sketch of an unconformity

Unconformities are usually worth drawing since they record information on major disturbances in sedimentary sequences. Figure 9.5 gives an example of how to draw an unconformity and shows a famous locality at Siccar Point in Scotland that Hutton used to demonstrate the concepts of geological time. In drawing unconformities the topography of the surface and the angular relationship between the older and younger units are the most important features to record. The sedimentary features of the units, such as bed lithology, thickness, and geometry, and any structures are, however, also important to include.

Observation of the outcrop is the first task. The unconformity here is marked by a change in the orientation of bedding, and is thus an angular unconformity. The underlying strata consists of Silurian interbedded slate and greywacke. Bed thickness of the greywacke varies considerably and is up to 40 cm in width. The greywacke, as the more competent lithology, protrudes from the surface with the slate weathered inwards to form grooves. Overlying the unconformity are Devonian red sandstones with beds 1–10 cm in width. Some poorly-developed trough cross-lamination is observed in some of the beds. The unconformity is a truncation surface; however, it is not entirely planar with greywacke beds penetrating up to 15 cm into the overlying sandstones. On the right of the image, a packet of greywacke beds is present that truncates the extension of the unconformity, indicating a topography of up to 70 cm on the surface. The overlying sandstone beds also slightly onlaps onto the surface.

Once the field of view and size of sketch have been chosen, the initial stage of drawing needs to captures the geometry of the unconformity.

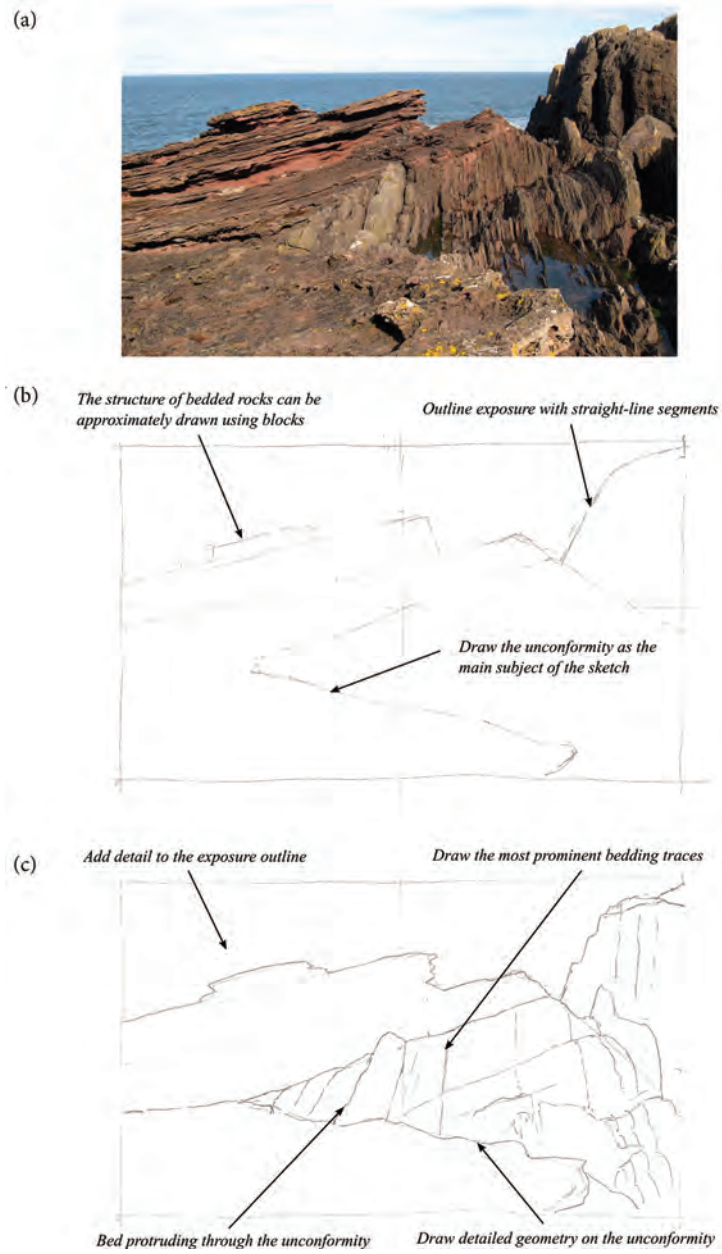
(a)
(b)
The structure of bedded rocks can be approximately drawn using blocks
Outline exposure with straight-line segments
Draw the unconformity as the main subject of the sketch
(c)
Add detail to the exposure outline
Draw the most prominent bedding traces
Bed protruding through the unconformity
Draw detailed geometry on the unconformity

Figure 9.5 Initial stages of a sketch of Hutton's unconformity at Siccar Point, Scotland (photo credit: Dave Souza)

The key lines to be drawn are the bedding traces and the unconformity surface. The outline of the exposure is also important to record and its topography is controlled in part by the bedding. Simplified straight lines allow the drawing to be blocked-in with points, such as the peak and steps on the platform of sandstones and the wave-cut gully on the right, positioned with help of the quadrant grid. Some of the bedding traces within the sandstone can also be added at this stage since they help identify the location of the unconformity. Finally, the unconformity can be added since it is the main subject of the sketch. In the distance its trace dips slightly more steeply than the bedding in the red sandstones, revealing the slight onlap. In the foreground it sweeps towards the right underneath a sandstone bed in the foreground, as shown in Figure 9.5b.

The simplified straight lines now need to be made more accurate by the addition of the protrusions and in-cuts on the surface. Particularly important is the protrusion of a 40 cm wide greywacke bed into the overlying sandstone on the unconformity in the middle of the image. This also necessitates adding some of the major bedding traces within the underlying Silurian strata, particularly those that bound the thicker greywacke beds. Two topographic features can also be added to help with positioning of lines—a shallow gulley that runs through the Silurian strata and the rock pool to the left, as shown in Figure 9.5c.

Now that most of the important features have been drawn, additional bedding traces can be added to better illustrate the variation in bed widths. Where the bedding trace is indistinct, discontinuous, but not dashed, lines can be used to indicate the uncertainty. Some of the greywacke beds protrude significantly through the unconformity and their near vertical bedding surfaces can be seen. Drawing these three-dimensional beds is best achieved by adding the lines marking the upper and lower edge of their bedding surface (Figure 9.6a).

Although the sketch is now essentially complete some additional ancillary features can be added that add both realism and clarity. The upper surface of the sandstone bed on the wave-cut platform in the foreground has some subtle surface features that can be drawn to emphasize its geometry as a near planar sheet covering the surface. Joints on the surfaces of some of the greywacke beds can also be added since they provide an indication of the three-dimensional shape of these beds.

The final stage of preparation is to add labels, scale and looking towards direction. When inking-in the sketch emphasis can be placed

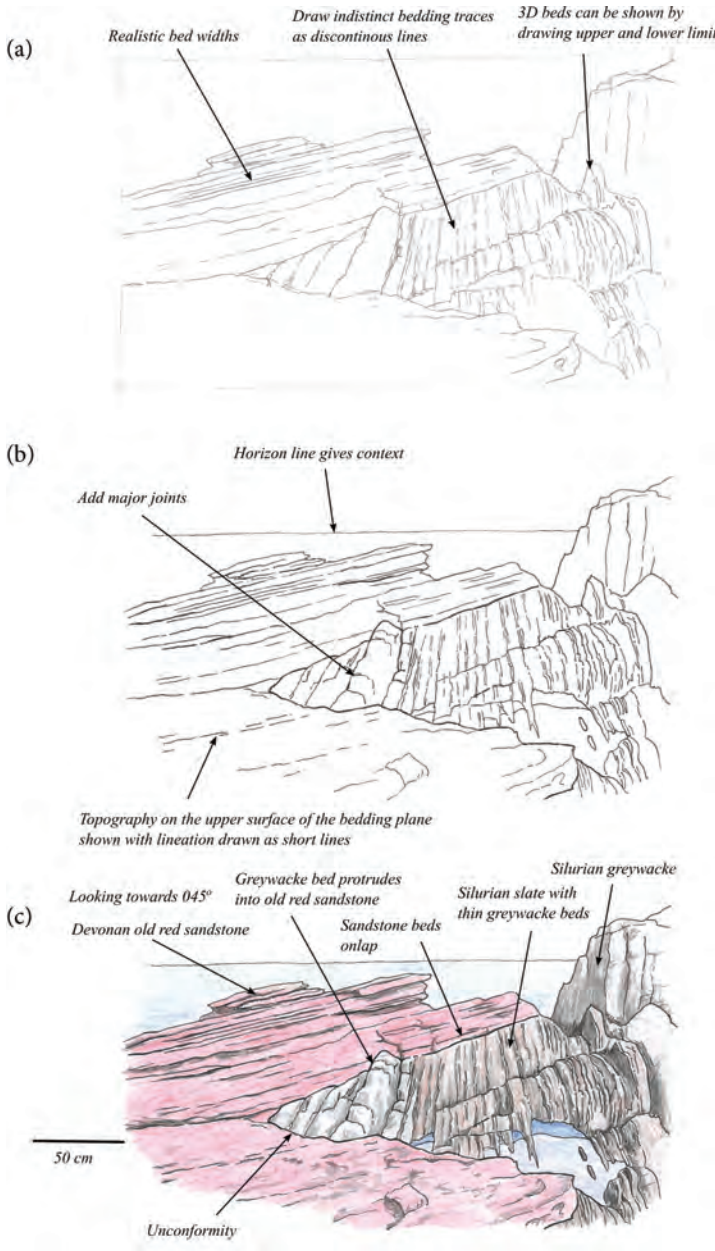
(a)
Realistic bed widths
Draw indistinct bedding traces as discontinous lines
3D beds can be shown by drawing upper and lower limits
(b)
Horizon line gives context
Add major joints
Topography on the upper surface of the bedding plane shown with lineation drawn as short lines
(c)
Looking towards 045°
Greywacke bed protrudes into old red sandstone
Silurian greywacke
Silurian slate with thin greywacke beds
Devonan old red sandstone
Sandstone beds onlap
50 cm
Unconformity

Figure 9.6 Final stages of a sketch of Hutton's unconformity.

on the most crucial feature, the unconformity, using slightly thicker lines. Colour also adds much to this sketch since there is important lithological variation—this also acts to highlight the bedding which is crucial in a sketch of sedimentary rocks. The colours are subtle in outcrop but can be exaggerated in the sketch to aid distinction between the rock types. Adding shading also is useful here since some of the beds are seen in three-dimensions and shading gives them volume. The finished sketch is shown in Figure 9.6c.

9.3 Sketch of a palaeokarst surface

Unconformities are not necessarily formed by long-term erosion and deformation; disconformities show no change in dip and are the result of shorter periods of non-deposition. In carbonate rocks exposure above sea level often results in the dissolution and the formation of a palaeokarst surface with a re-entrant irregular trace relative to the overlying sediments. A palaeokarst is shown in Figure 9.7 and is in the Jurassic Purbeck Group at Durdle Door in Dorset, UK. The white massive limestone at the bottom of the photograph has an irregular karstic upper surface and is overlain by laminated micritic limestones (lime mud) containing sparse bioclastic materials (broken shell fragments).

The outline of the exposure has no particular geological significance but provides a useful geometry by which significant features can be positioned relative to each other; it can thus be drawn first using simple straight lines. The most important bedding trace to include is the palaeokarst; however, laminations are also present in the overlying limestone that provide some sedimentological information. Darker bands in the limestone are particularly interesting since they may be more clay-rich. The major contacts between the dark and light layers in this limestone can also, therefore, be added whilst blocking-in, as shown in Figure 9.7b.

Detail can then be added to the simplified lines. The geometry of the palaeokarst is the most important feature to draw. It has numerous indents and protrusions, some of which are sharp and have overhangs of a few cm relative to the bedding plane. The laminations in the overlying grey limestone are also important. These are most easily seen at the boundary between the darker and lighter areas. During drawing it is noticed that some of the darker laminations are discontinuous, whilst lighter laminations within the grey limestone are lenticular in shape. Some prominent fractures can also be added to give more realism to the sketch (Figure 9.7c).

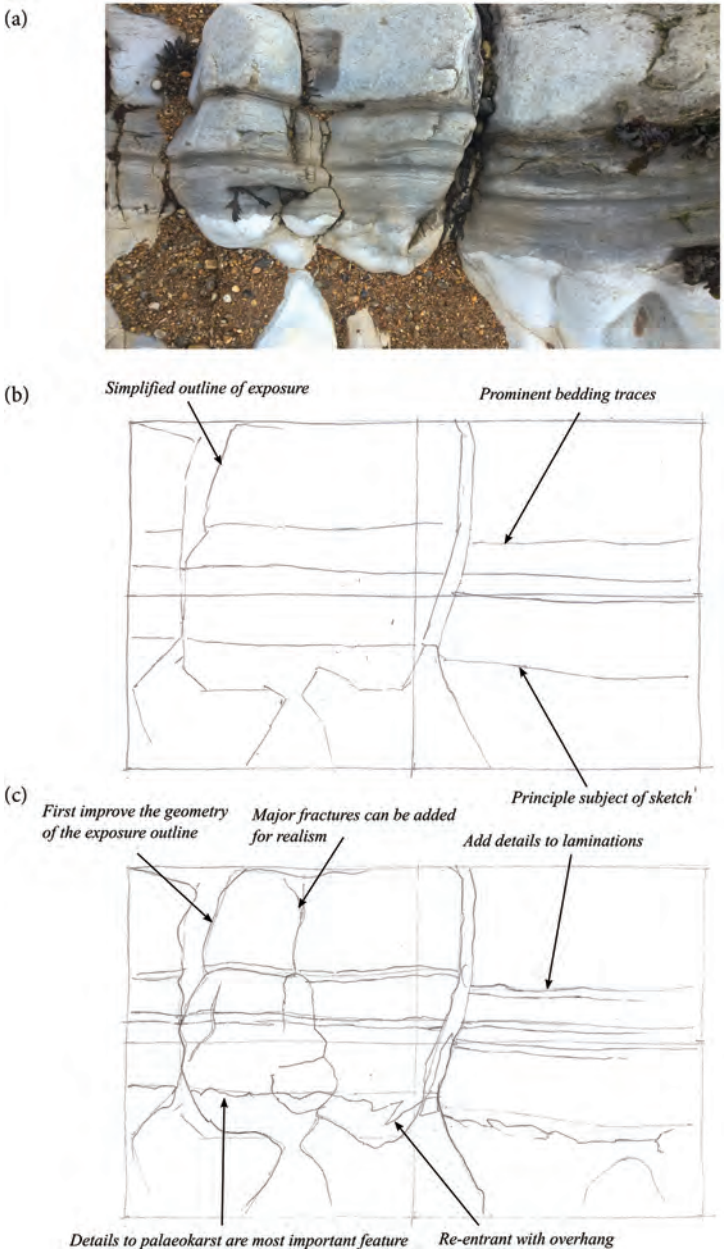

Figure 9.7 Initial stages of a sketch of a palaeokarst in the Purbeck Group at Durdle Door, Dorset in the UK.

The final task is to add scale, orientation, and labels. This outcrop is seen in plan view and thus a north arrow can be added for an orientation. Labels can describe lithologies and the nature of the palaeokarst surface. Interpretations can also be added. Here lenticular carbonate-rich and clay-rich limestone laminations occur overlying the karstic surface. The carbonate-rich lenticular bands may represent ripples of silt-grade carbonate grains within a finer-grained, clay-bearing lime mud. The elongate discontinuous band of darker limestones may represent mud-drapes over cm-sized ripples, as shown in Figure 9.8. These structures could indicate deposition on a carbonate mud-flat in an intertidal zone after the karst surface has been flooded. In the rest of the exposure stromatolites and halite pseudomorphs occur suggesting the environment was a hyper-saline lagoon with microbial mats present.

This sketch provides an example of a small-scale drawing that is useful in documenting some of the evidence required for facies analysis. Often at localities in which different beds exhibit different sedimentary structures and fossil assemblages a series of high resolution sketches, combined with a record of the overall sequence, provides a powerful means to record information that relates to the sedimentary facies.

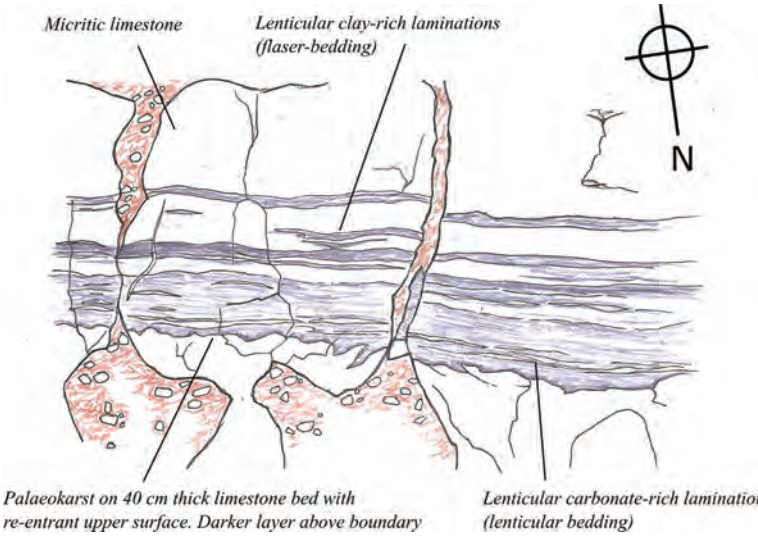
Micritic limestone
Lenticular clay-rich laminations (flaser-bedding)
N
Palaeokarst on 40 cm thick limestone bed with re-entrant upper surface. Darker layer above boundary
Lenticular carbonate-rich laminations (lenticular bedding)

Figure 9.8 Completed sketch of a palaeokarst in the Purbeck Group.

9.4 Drawing cross-stratified sandstones

Siliclastic units with cross-bedding are challenging to sketch, owing to the number of significant surfaces to be drawn and the variable geometries of truncations between sets. A cross-bedded Triassic sandstone exposure from Sardinia in Italy is shown in Figure 9.9 and features trough cross-stratifications on several different scales. Small lags of conglomerate are also present. The scale of foresets, truncation geometries, and the spatial relationships between the cross-lamination and conglomerate lags are important to record within this sketch.

The outline of the outcrop provides a useful shape by which the geological features can be positioned within the sketch. The outcrop is broadly rectangular except for its upper surface, which reaches a maximum height about three quarters of the way across the top left quadrant. On the right the outline is re-entrant with several beds protruding outwards. The lower surface dips down towards the left. All these features can be added initially as straight lines. The most prominent bedding traces can also be included. Some of these prominent lines will represent master surfaces between separate cosets of trough cross-stratification (Figure 9.9b).

Now that the overall geometry of the sketch has been established, the simple straight lines can be refined by adding detail. Some of the main trough set boundaries can also be drawn at this stage, particularly the larger prominent troughs in the upper part of the outcrop. The shape of these larger sedimentary structures will help in the positioning of the smaller structures and their fine detail.

The next step in the sketch is to add the boundaries of all the troughs where they truncate other sets. These curves can then be used as guides to add the foreset laminations since these are sub-parallel. Laminations can be added as discontinuous lines where they are difficult to see. Finally, the conglomerate clasts can be added. In several places these are lags along master or reactivation surfaces, however, they are also dispersed throughout some troughs. Clasts are difficult to include realistically in this sketch owing to their small scale relative to the outcrop as a whole and thus some exaggeration of their size is necessary. The shapes of clasts should, however, be drawn as realistically as possible, as shown in Figure 9.10a.

A particularly interesting conglomerate lag exists in the middle of the outcrop and is dominated by sub-rounded vein quartz clasts. It is clast-supported and contains very-coarse sand as a matrix between the clasts.

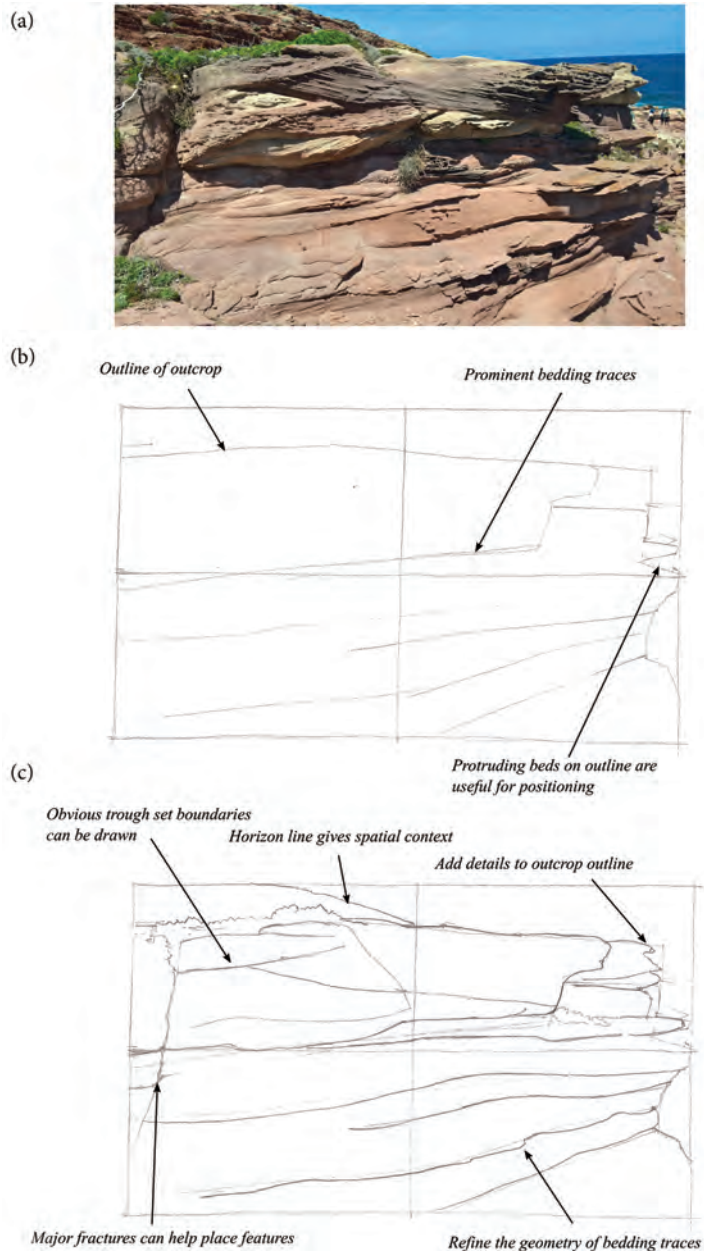
(a)
(b)
Outline of outcrop
Prominent bedding traces
Protruding beds on outline are useful for positioning
(c)
Obvious trough set boundaries can be drawn
Horizon line gives spatial context
Add details to outcrop outline
Major fractures can help place features
Refine the geometry of bedding traces

Figure 9.9 Initial stages of a sketch of cross-stratified Triassic sandstones and conglomerates from northwest Sardinia, Italy.

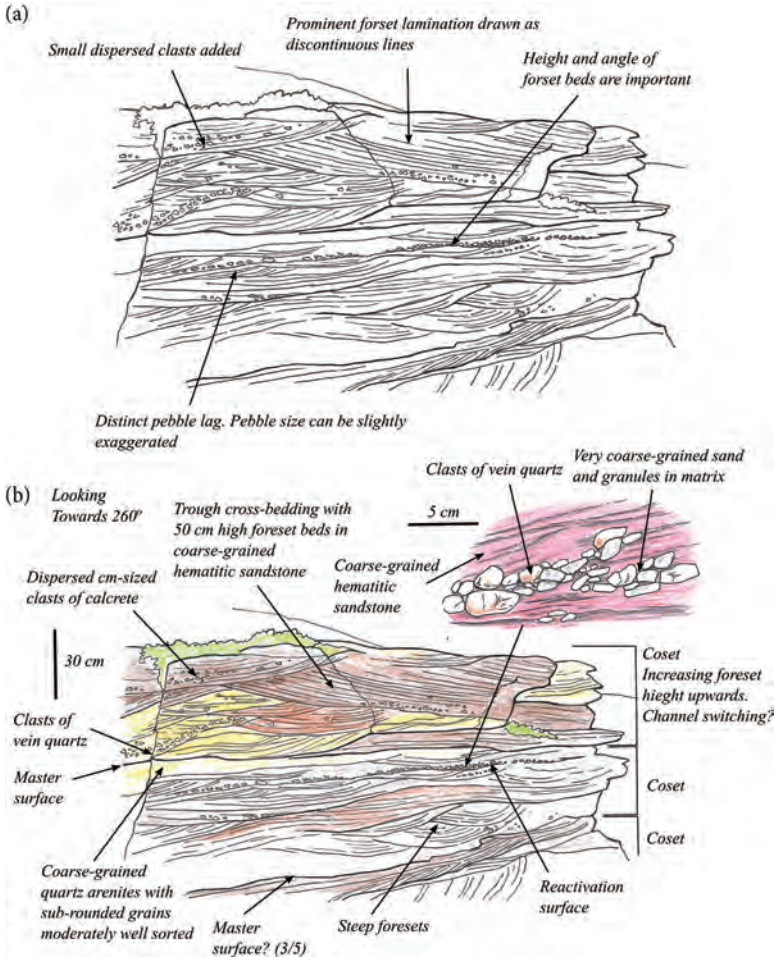
(a)
Small dispersed clasts added
Prominent forset lamination drawn as discontinuous lines
Height and angle of forset beds are important
Distinct pebble lag. Pebble size can be slightly exaggerated
(b)
Looking Towards 260°
Trough cross-bedding with 50 cm high foreset beds in coarse-grained hematitic sandstone
5 cm
Clasts of vein quartz
Very coarse-grained sand and granules in matrix
Coarse-grained hematitic sandstone
Dispersed cm-sized clasts of calcrete
30 cm
Coset
Increasing foreset hieght upwards. Channel switching?
Clasts of vein quartz
Master surface
Coset
Coset
Coarse-grained quartz arenites with sub-rounded grains moderately well sorted
Master surface? (3/5)
Steep foresets
Reactivation surface

Figure 9.10 Final stages of a sketch of cross-stratified sandstones and conglomerates.

The clast-supported nature and the removal of finer sand from between clasts may suggest this lag formed as a result of winnowing by wind and is a deflation lag (a desert pavement). This would suggest a period of wind-erosion under arid conditions. An inset diagram, drawn at higher scale, can be used to illustrate the nature of the conglomerate since it has significant implications. Particular attention is given here to ensuring shape and relative sizes of the clasts are accurate. Inset diagrams are very useful in recording sedimentary rocks that have significant features

on multiple scales and should be linked to the main diagram using arrows or labels. Knowing exactly where in the outcrop these higher resolution observations were made is very useful in interpretation.

All that remains is to add scale, looking direction, and labels. The labels should include descriptions, but can also be interpretive. There is an increase in the scale of cross-beds upwards above a distinct master surface. Although the sedimentary facies is not obvious in this one outcrop, the rest of the unit suggests these are braided-river deposits. The increase in trough size suggests an increase in water depth, perhaps owing to switching of flow between channels. The deflation lag implies that the earlier small channel dried out and underwent aeolian erosion. The finished sketch is shown in Figure 9.10b.

9.5 Drawing ripple marks

Drawing sedimentary structures on bedding surfaces provides useful insights into current direction and changing flow regimes, but is complicated by their three-dimensional nature. Ripple marks are common in the geological record and sketching them is made more difficult since their surfaces are often relatively smooth and they can lack distinct lines to draw. A bedding plane decorated by ripple marks and casts of sponges from King's Canyon in Australia is shown in Figure 9.11a. The ripples show variable development over the surface and change in morphology from one place to another. In addition to the sponge clasts, smaller sets of ripple marks are also present.

The complexity of this outcrop requires special care when blocking-in features. Since there is no particular outline to the exposure, other features must be used to provide guides by which the ripples can be positioned. The ripple marks are present in several areas and although these do not have distinct boundaries their shapes can be interpolated by eye. Drawing the shapes of the areas containing ripples first provides a framework by which the detailed features can be added, as show in Figure 9.11b. The outlines of the sponge casts can also be drawn at this stage since these are unusual features to be preserved.

Drawing the larger sets of ripple marks is difficult owing to the lack of distinct lines or boundaries. Several shapes of ripple are present. Some have distinct crests, which although somewhat rounded, can be followed and drawn as lines. Often these ripples have obvious steep lee-sides and the bottom of the lee-slope can be added as a line. Other ripples have flat, truncated crests and on either side have sinuous small

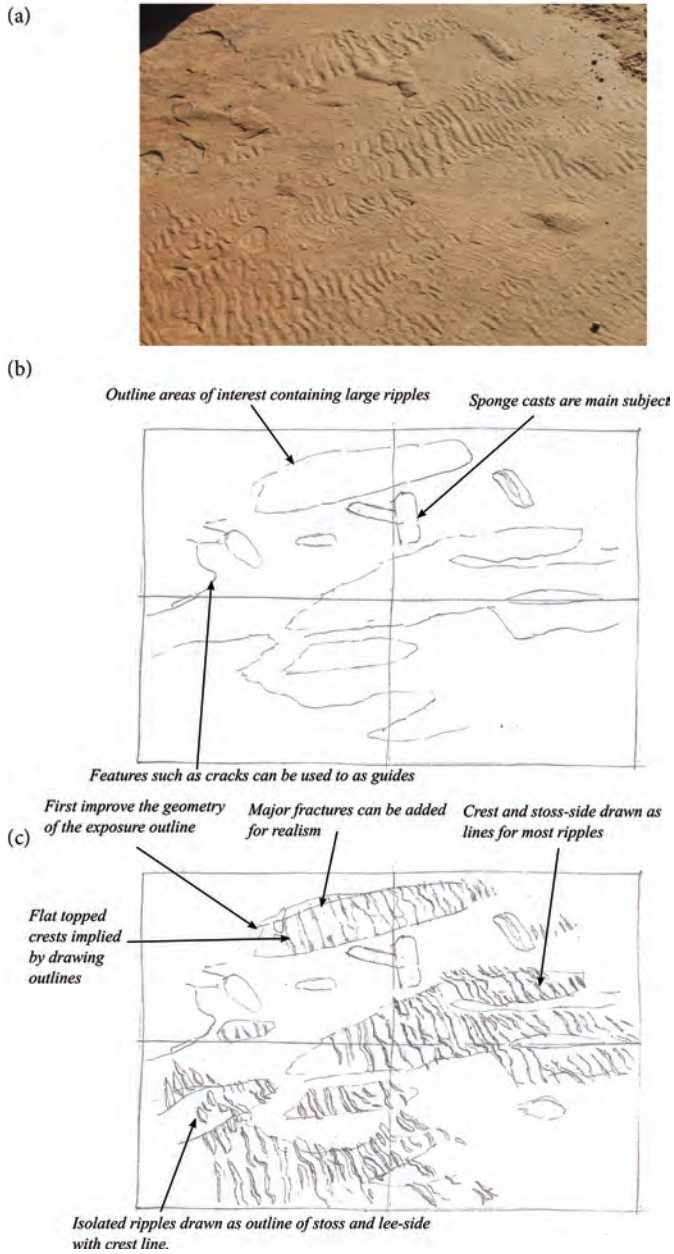
(a)
(b)
Outline areas of interest containing large ripples
Sponge casts are main subject
Features such as cracks can be used to as guides
(c)
First improve the geometry of the exposure outline
Major fractures can be added for realism
Crest and stoss-side drawn as lines for most ripples
Flat topped crests implied by drawing outlines
Isolated ripples drawn as outline of stoss and lee-side with crest line.

Figure 9.11 Initial stages of drawing of ripple marks exposed on a bedding plane in Triassic sandstones at Kings Canyon, Australia.

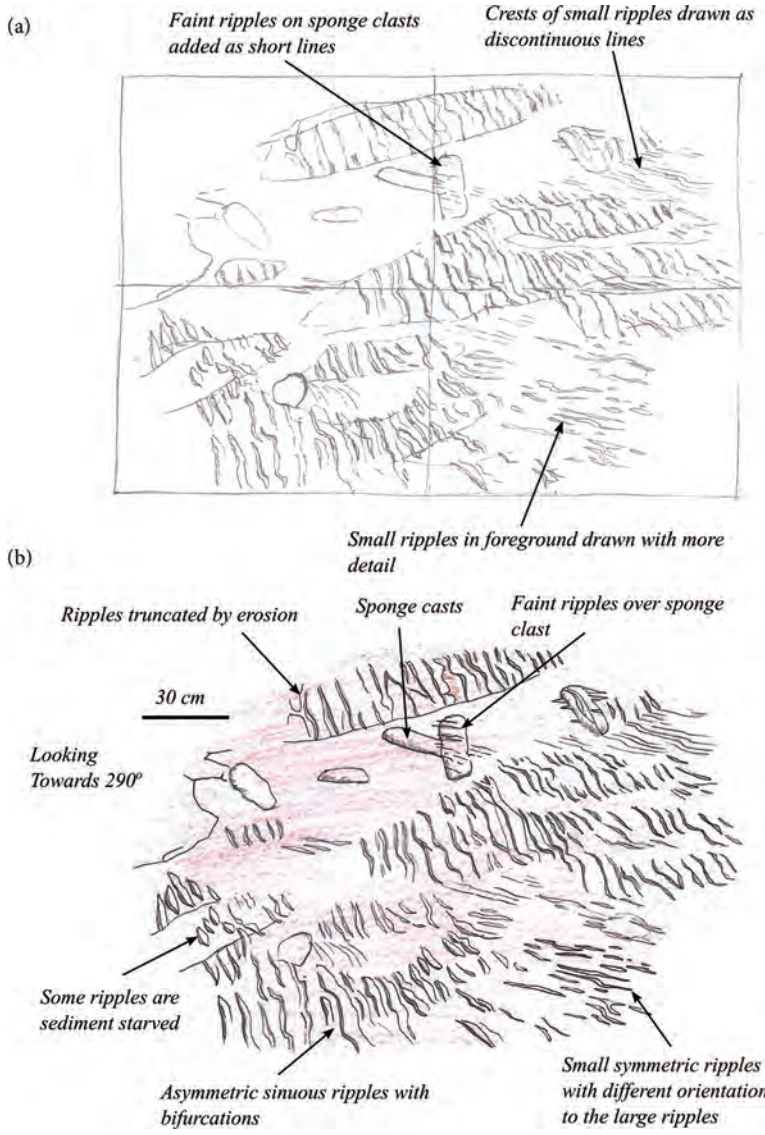
(a)
Faint ripples on sponge clasts added as short lines
Crests of small ripples drawn as discontinuous lines
Small ripples in foreground drawn with more detail
(b)
Ripples truncated by erosion
Sponge casts
Faint ripples over sponge clast
30 cm
Looking Towards 290°
Some ripples are sediment starved
Asymmetric sinuous ripples with bifurcations
Small symmetric ripples with different orientations to the large ripples

Figure 9.12 Final stages of drawing of ripple marks.

gulleys, formed by the base of the lee and stoss slopes. Drawing the outline of these small gulleys gives the impression of a flat-topped ripple. Finally, on the lower right, some of the ripples form short lenticular bodies. The shape of these can be outlined and the crest added to record their shape, as shown in Figure 9.11c.

The final stage (Figure 9.12) of the sketch is to add scale, orientation, and labels. The larger ripples here are probably wave ripples despite their asymmetric shapes. The presence of sponge casts indicates a marine environment and the flat crests of some of the ripples are likely to have been caused by erosion owing to the complex nature of the wave currents. This interpretation implies water depth is above the fair-weather wave base. The symmetrical ripples indicate some change in current, potentially by wave directions during lower wind conditions being influenced by a nearby coastline.

9.6 Sketch sedimentary logs

Sedimentary logs are often used to document sequences of sediments and are graphical representations of the stratigraphy that include lithology, sedimentary structures, bed and unit thickness, and the fossils present. They emphasize the vertical change in the sediments, but contain only limited information on their lateral change.

There is no standard format for a sedimentary log; however, they usually consist of a stratigraphic column split into a lithology column, which represents rock type using symbols, and a texture column that graphically documents sedimentary structures. The width of the texture column varies depending on the average grain size of the sediment producing a grain-size curve. Other features, such as bedding plane structures and fossils, are usually drawn as symbols adjacent to the corresponding bed. Finally, descriptions of each unit, in particular those not included elsewhere in the diagram, such as composition, sorting, grain shapes, and interpretative comments, are recorded in adjacent columns, as shown in Figure 9.13.

Typically, sedimentary logs are constructed in the field by measuring the thickness of each layer with a tape measure and involve close observation of lithology layer by layer. Often they are recorded on pre-prepared log paper on which the columns are already printed. Since the objective of a log is to show the change in sediment characteristics through a sequence, exposures that include the most complete sections through the stratigraphy are documented.

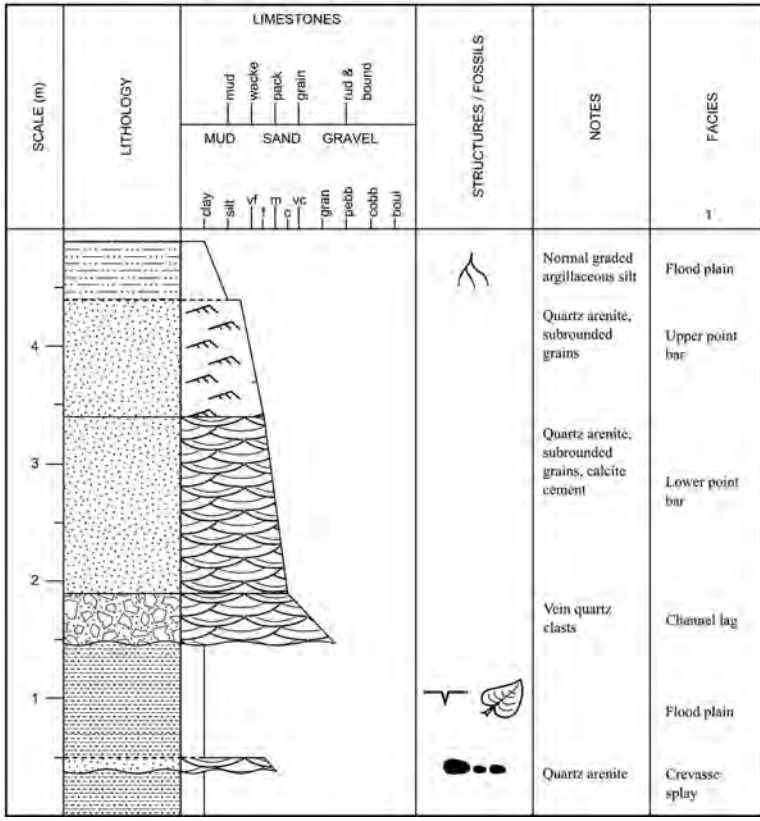

Figure 9.13 A sedimentary log showing meandering river deposits (created using SedLog by Royal Holloway).

In addition to their use in recording observations of sedimentary sequences, schematic logs are often used to illustrate sedimentary facies, as shown in Figure 9.4. These diagrams, which are intended to summarize and communicate complex stratigraphic relationships, often lack separate lithology and sedimentary structure columns, and instead can use colour to indicate lithology in combination with the grain-size curve. Such schematic logs can be likewise used within field notebooks to summarize a sequence observed over several localities. Summarizing disparate observations within separate interpretation sections of a notebook is useful in conceptualizing the stratigraphic relationships between units observed in the field, particularly during geological mapping.

Often outcrops expose too little of the sedimentary sequence to make them useful in constructing a detailed log of the stratigraphy. Logs can, however, be useful in recording their sedimentary features and provide an alternative to a field sketch of the entire exposure. These sketch sedimentary logs can be constructed quickly, like a field sketch, by estimating thicknesses, followed by an assessment of grain size, fossil assemblage, and bedding plane features.

An example of a sketch log is given in Figure 9.14 and shows an outcrop of Nubian Sandstone in the southwestern desert of Egypt. The log shows the two packets of pale pink sandstone at the bottom of the outcrop with low angle trough cross-stratification. Between the two pink layers is an ochre coarse-grained sandstone with steep planar foreset beds. Above the pink sandstones is a thin lens of clast-supported conglomerate overlain by ochre cross-bedded sandstones that fine upwards to a thin, indistinct mudstone. Finally, at the top of the outcrop is a matrix supported granule conglomerate.

A log provides a convenient means of recording the lithological and structural change in this outcrop. Sedimentary structures can be added to the log by drawing them as realistically as possible, and to scale, so that foreset height need not be described separately. A sketch log can be generated in a few minutes and then descriptions added whilst inspecting lithologies at the rock face.

It is not always possible to make a conclusive and rigorous interpretation at every outcrop; however, even simple deductions such as current direction, flow velocity or estimated water depth are useful to record. In this case, the steep planar foresets with heights of ~1 m are likely to have been deposited by aeolian dunes. An aeolian origin for the pink sandstones can also be suggested on the basis of the spherical nature of their sand grains. The overlying ochre sediments begin with a basal conglomerate with a lenticular shape suggesting that it is a fluvial channel lag. The overlying packet of trough cross-stratified sandstones fine upwards and may represent dunes within a river channel, or potentially the lateral accretion of a point bar. These interpretations can be added to the log.

Sketch logs are useful where exposure of a sedimentary sequence is limited to smaller outcrops since they provide a higher resolution means of recording the stratigraphy than written descriptions, but are quicker to produce than field sketches. The combination of sketch logs from a series of outcrops may allow a more complete stratigraphy to be constructed, particularly if characteristic marker beds are identified. The

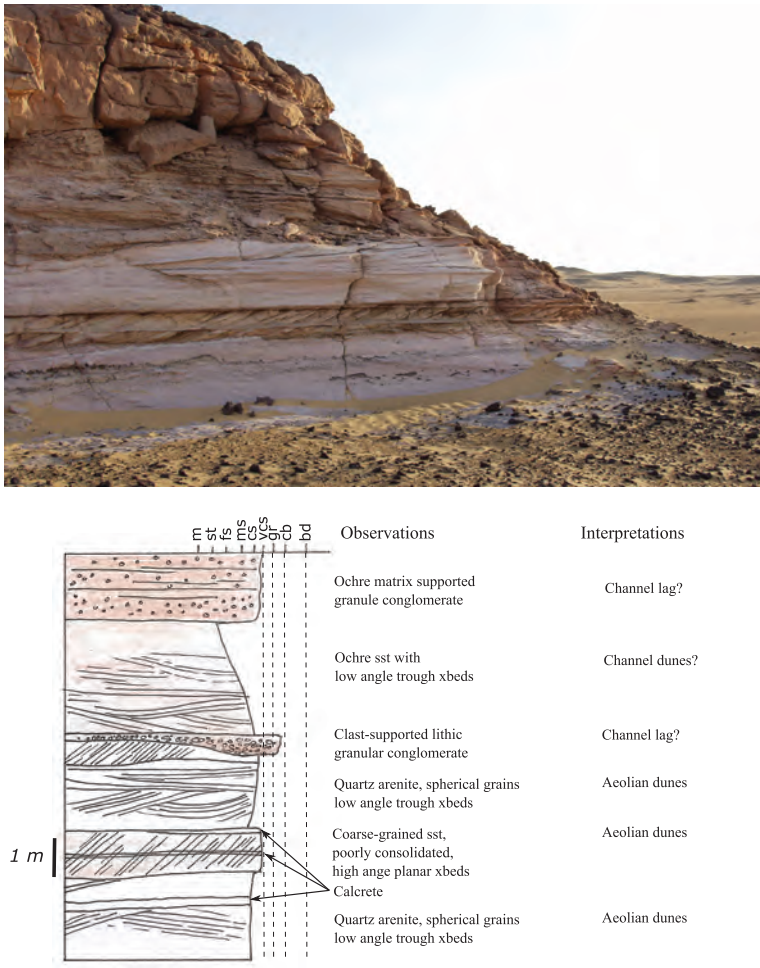

Figure 9.14 A sketch sedimentary log of an outcrop of Numidian Sandstone from the southwestern desert of Egypt.

data from numerous logs will also provide more confident interpretation of sedimentary environments.

9.7 Common mistakes

The commonest mistake in drawing sedimentary rocks is to use a symbolic patterns to represent lithology, such as dots to represent sand-

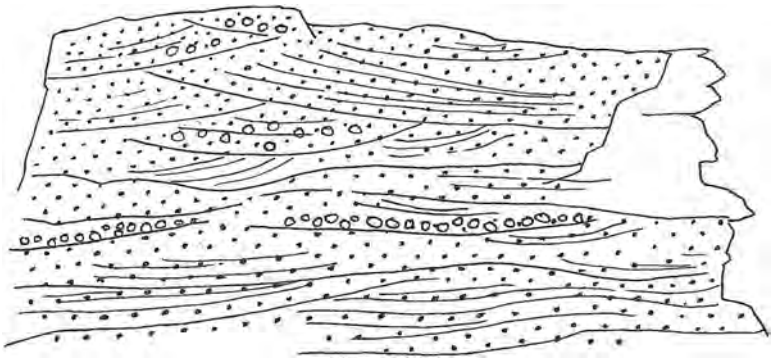

Figure 9.15 An example of the over-use of symbolic patterns to represent lithology.

stone, circles for conglomerates, or brickwork patterns for limestone, as shown in Figure 9.15. Symbolic patterning was commonly used in publications and textbooks as a cheaper alternative to colour printing, but is not necessary in field notes. Patterns introduce features into diagrams that do not exist. They also tend to obscure the detail of geological structures.

9.8 Key concepts

The most important considerations when drawing sedimentary rocks are as follows:

- Bedding is the most important feature to record and guides the geometry of a sketch. Care should be taken to show changes in thickness of beds vertically and laterally as well as non-planar bedding contacts that may be erosional features.
- Sedimentary structures, in particular cross-stratification, should be drawn as accurately as possible; focusing on the most important planes such as the boundaries between individual sets, cosets, and master surfaces.
- Clast shapes, sizes, and abundances should be drawn realistically and only simplified where there are too many to be represented.

- Higher resolution peripheral diagrams provide an excellent means of recording important small-scale features within sedimentary outcrops.
- Lithological descriptive labels are important in recording sedimentary rocks and should be as quantitative as practical.

10

Drawing fossils

Fossils are a crucially important component of sedimentary rocks since they provide a means of constraining the age of strata through biostratigraphy. Recording the fossil assemblage present is thus vital. Often, however, there is no reason to draw fossils in the field since they can be adequately recorded with scaled and oriented photographs, or through the collection of reference samples. When fossils cannot be collected, owing to difficulty in their extraction or because the locality is protected, and photographs are less than optimal, then it is worth drawing fossils. A particularly important consideration is preservation since trying to remove the one exceptional quality specimen from an exposure is fraught with risk to the specimen and is a form of geological vandalism. Such valuable specimens can be recorded using photogrammetry, as described in Chapter 16. Often then it is fossils that are not perfect examples, and thus not worth collecting, or fossils that are in situ that will be drawn.

Drawing fossils is complicated by their often regular geometric forms. Small errors in drawing irregular shapes, such as the outline of an exposure, matter little; however, they are obvious when sketching something as regular as a fossil. Detail is also a crucial consideration since fossils can preserve morphological features on a wide range of scales that are difficult to include in a single sketch. Finally, as in all geological sketches, drawing fossils involves recording the most important features, which requires knowledge of their taxonomy. In this chapter an approach to drawing fossils is described that involves blocking-in of their geometry, followed by sequential addition of levels of detail. Techniques in illustrating the three-dimensional nature of fossils are also described.

10.1 Common fossils

Every geologist needs a working knowledge of palaeontology. The ability to identify the phylum and class of fossils is essential in order to evaluate the palaeoenvironment of sedimentary rocks, in particular in providing

Geological Field Sketches and Illustrations: A Practical Guide. Matthew J. Genge, Oxford University Press (2020).
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information on water depth, salinity, current, and sedimentation rate. Identification to an order, family or genus level is often necessary in mapping to enable biostratigraphic analysis and can be achieved with proper literature preparation. Evaluation of fossils to the species level is a specialist task not generally undertaken except by palaeontologists.

A summary of the fossils most commonly encountered by geologists is shown in Figure 10.1 together with some important elements of their taxonomy. Every geologist should be familiar with this list of fossil phyla and classes, together with their range in the geological record. Fossil occurrence depends on both depositional environment and subsequent diagenetic preservation factors. In terms of environment, sub-aerial sediments are often poorly fossiliferous except for freshwater molluscs or land gastropods, which tend to be thin-shelled. Plant fossils are more common but are often poorly preserved except under ideal conditions, rendering only small and difficult to identify fragments. Fossil wood, however, is relatively common but has little biostratigraphic significance except for some specific genera. Some plants can be useful, for example, *Calamites* tree ferns and *Lepidendron* club mosses in Carboniferous sequences.

Fossils are more useful in marine and estuarine sequences. Molluscs and brachiopods are usually present in most environments except in deep abyssal sediments with brachiopods more abundant in Palaeozoic sequences and molluscs in Mesozoic to recent sediments. In highly saline environments gastropods also tend to be absent whilst bivalves have low diversity. Throughout most of the Phanerozoic stromatolites are also indicative of saline conditions since they are sensitive to predation by grazing organisms such as echinoids and gastropods both of which tend to be intolerant of high salinity. Echinoids are widespread and are present in abyssal sediments, at least after the Palaeozoic. Crinoids too can be present in deep water sediments, not least since they can be planktonic through attachment to floating rafts, although this is rare.

Pelagic organisms, which are those living in the open oceans, such as ammonites and belemnites, are widespread and can be found in deep and epicontinental marine sediments. They are, however, present in low abundances in small or restricted ocean basins. Whether pelagic organisms are active swimmers or planktonic influences their distribution owing to concentration or exclusion by currents. The widespread nature of many pelagic organisms often makes them useful in biostratigraphy.

Reef-building organisms are particularly important in the geological record since they create carbonate factories that produce much of the material found in limestones, at least prior to the evolution of carbonate secreting plankton. Reefs are also complex ecosystems that support a

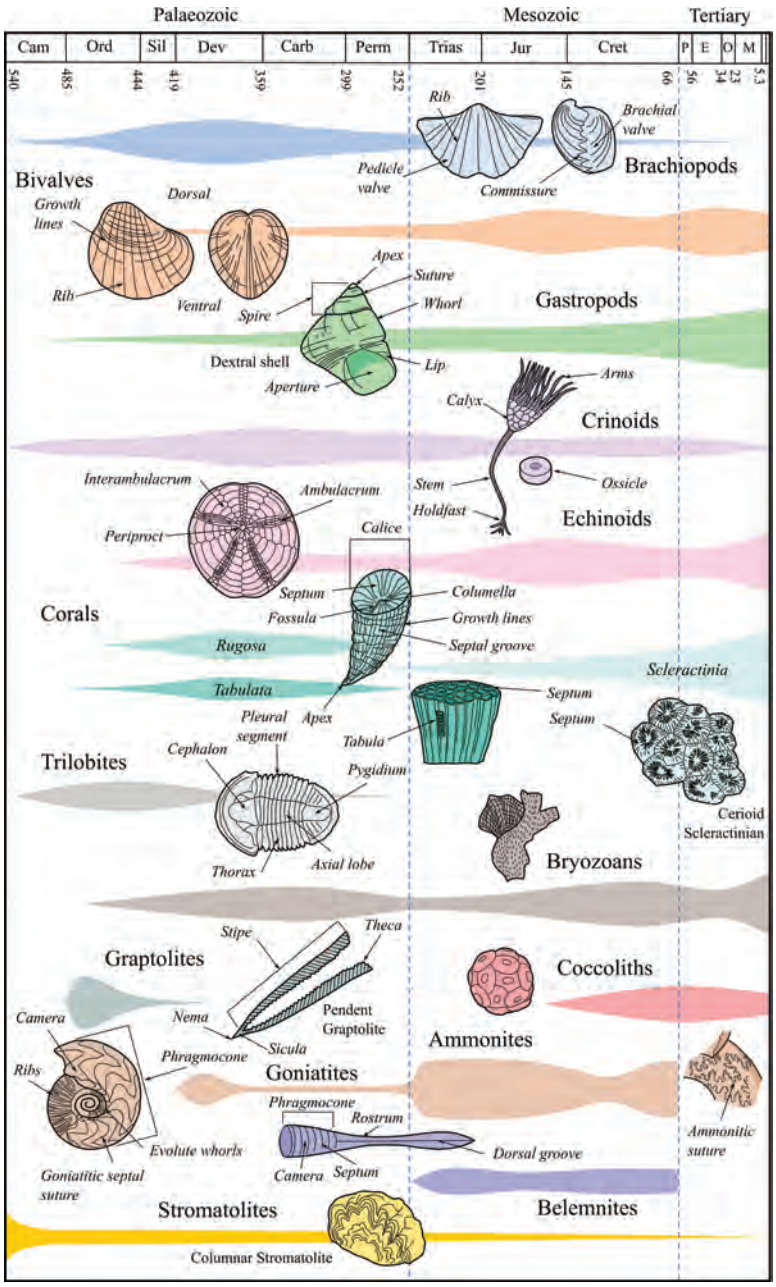

Figure 10.1 A summary of common fossil phyla and classes together with their abundance in the geological record and elements of taxonomy.

high density of marine organisms and may increase evolutionary diversification. The topographic effects of reefs furthermore result in changes in the distribution of depositional environments, with lagoon environments produced by atolls and barrier reefs. The organisms that have generated reefs have changed with geological time, with Archaeocyatha and stromatolites important in the Cambrian, corals from the orders Rugosa and Tabulata from the Ordovician to the Permian, and corals from the order Scleractinia dominant from the Mesozoic to the present. Rudist bivalves have also been important reef-building organisms, in particular in the Cretaceous. Reefs are also sensitive indicators of climatic change and are particularly prone to extinctions.

The appearance and extinction of some classes and orders of fossils is particularly useful in coarse biostratigraphy in the field. Planktonic graptolites, for example, are restricted to the Ordovician and Silurian and became extinct in the Devonian. Trilobites are also restricted to the Palaeozoic and are primarily benthic organisms that range from Cambrian to late Permian in age. In contrast ammonites and belemnites are characteristic of Mesozoic open marine sediments and became extinct at the end of the Cretaceous. However, morphologically similar ammonoids such as goniatites did exist in the Palaeozoic and differ in their simpler sutures, whilst nautiloid cephalopods occur throughout most of the Phanerozoic; the most commonly found, the straight cone-like chambered shells of forms such as Orthoceras, superficially resemble belemnites. Coccoliths are included in Figure 10.1 although these are microfossils since they are the principle component of chalk and thus readily identified by the occurrence of this rock type. Coccoliths evolved in the Triassic and are extant today.

Vertebrate fossils are rare in comparison to invertebrates and are rarely encountered by most geologists. Fish teeth are perhaps the most common vertebrate fossils and can be found in great numbers in some marine sediments. Marine reptile and shark vertebrae are also occasionally encountered particularly within Mesozoic strata.

10.1.1 Ichnofossils

Ichnofossils (trace fossils) are also very important tools in palaeoenvironment interpretation and their major types are shown in Figure 10.2. Burrowing organisms generate bioturbation and are a particularly important indicator of oxygenated seafloor conditions and are usually absent under anoxic conditions. Bioturbation is widespread in the geological

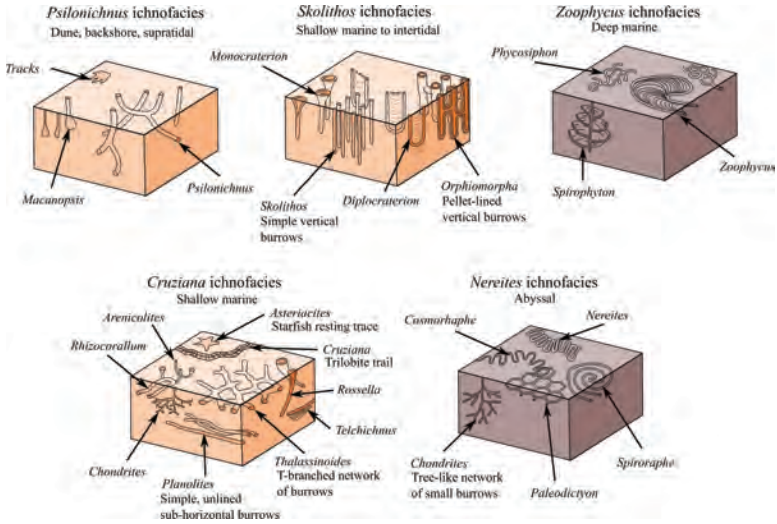

Figure 10.2 Common ichnofossils by environment.

column and can be generated by soft-bodied invertebrates, such as worms, shelled invertebrates such as molluscs, echinoids, and crustaceans, or more rarely vertebrates. Assemblages of trace fossils can be characteristic of types of environment and form ichnofacies, as shown in Figure 10.2.

10.2 Fossils in life position

Often the most valuable sketches of fossils are those that illustrate their sedimentological context. Spatial relationships are particularly important when fossils are preserved in their life position. Most commonly this is observed for reef-building organisms such as corals or stromatolites, tree boles on palaeosols, or organisms encrusting surfaces, such as marine hardgrounds. In the example shown in Figure 10.3 a tree fern is present within lacustrine deposits. It survived several falls of volcanic ash, represented by the thin green layers of tuff. This outcrop is Upper Carboniferous in age and is from the Spanish Pyrenees.

The objective of the sketch is to illustrate the relationship between the sedimentary sequence and the tree fern fossil. The problem with this outcrop is the limited exposure, owing to a covering of scree, which means that the surrounding rocks only occur in patches that make it difficult to extrapolate bedding. The distribution and shape of the small

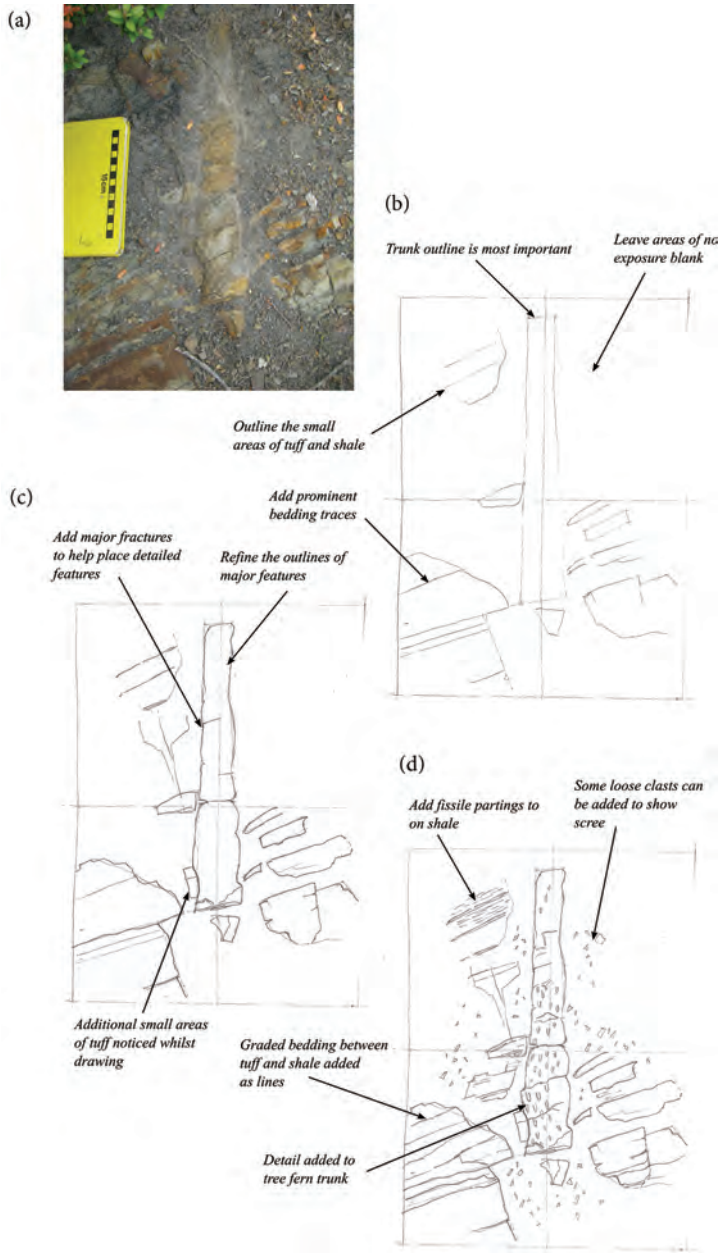
(a)
(b)
Trunk outline is most important
Leave areas of no exposure blank
Outline the small areas of tuff and shale
(c)
Add prominent bedding traces
Add major fractures to help place detailed features
Refine the outlines of major features
(d)
Add fissile partings to on shale
Some loose clasts can be added to show scree
Additional small areas of tuff noticed whilst drawing
Graded bedding between tuff and shale added as lines
Detail added to tree fern trunk

Figure 10.3 Initial stage of sketching of a tree fern in life position from the Spanish Pyrenees.

exposures, however, can be drawn in the initial blocking-in stage of the sketch using simplified straight lines shown in Figure 10.3b. This includes the fern trunk, which is essentially rectangular in outline with a slight taper towards the top of the image. The most prominent bedding traces can also be added at this stage.

Improving the accuracy of existing lines is the next task in drawing. The trunk is the main subject of the sketch and is thus the most important feature to draw accurately. Close inspection reveals the width changes along its length producing several ring-like protrusions. There are also some major fractures cutting across the trunk. Some additional areas of exposure of mudstone and tuff surrounding the trunk are also noticed during this stage of sketching and can be added, as shown in Figure 10.3c.

With accurate outlines bounding the most important objects, detail can then be drawn. On the fossil elongate elliptical protrusions occur and are arranged in a diamond-like pattern. These protrusions probably mark the attachment of leaf fronds and are petiole bases; the diamond-like arrangement is described as *Caulopteris* and suggests the fossil belongs to the genus *Parsonius*.

Bedding traces within the small areas of exposure surrounding the fossil are gradational from tuff to mudstone. This sequence is overturned and thus the mudstone is concentrated at the top of each layer and tuff at the bottom. The indistinct traces can be drawn as discontinuous irregular lines (Figure 10.3d).

The final tasks are to add scale, orientation, and labels, as shown in Figure 10.4. The morphological features of the trunk are important to label to demonstrate the taxonomy and the genus. Labels are also needed for the lithological features of the surrounding rocks. The presence of black to grey mudstones together with the fern suggests a swamp—in fact elsewhere in the formation coal seams occur. The presence of tuffs indicates nearby volcanic centres with explosive eruptions that emplace air-fall ashes into the swamp. Settling of ash through the water results in the observed normal grading in some layers. Way-up, suggested here from grading bedding and supported by constraints from the local geology, can be indicated by adding an inverted Y symbol with the base of the symbol pointing towards the older strata. Colour is very useful in this sketch to illustrate the lithological variation.

A particularly important interpretation is that the fern penetrates through 60 cm of sediment. Close to the fern some of the layering folds stratigraphically upwards, possibly as a consequence of continued growth

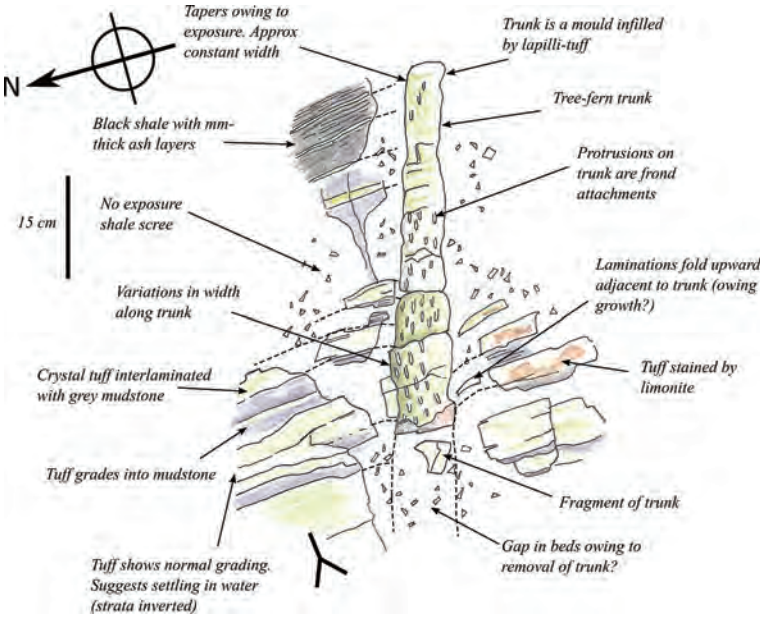
N
Tapers owing to exposure. Approx constant width
Trunk is a mould infilled by lapilli-tuff
Tree-fern trunk
Black shale with mm-thick ash layers
Protrusions on trunk are frond attachments
15 cm
No exposure shale scree
Laminations fold upward adjacent to trunk (owing to growth?)
Variations in width along trunk
Crystal tuff interlaminated with grey mudstone
Tuff stained by limonite
Tuff grades into mudstone
Fragment of trunk
Gap in beds owing to removal of trunk?
Tuff shows normal grading. Suggests settling in water (strata inverted)

Figure 10.4 Finished sketch of a tree fern in life position.

of the plant. A gap in the beds below the fossil, together with small pieces of fern in the area, suggest it extends through the thicker tuffs at the top of the observed sequence (bottom of the image). Regular dashed lines can be added to show these extrapolated boundaries. The fern is preserved as a mould in-filled by lapilli-tuff that is coarser-grained than the surrounding tuffs and must have fallen in from above as the plant decayed.

10.3 Preservation state

Recording the state of preservation of fossils can be an important aim of a field sketch. Whether shells are preserved as moulds or casts can relate to whether the shells were originally calcite or aragonite, with aragonite most likely to be removed by dissolution. The occurrence of bivalves as disarticulated values (i.e. a single valves) also provides evidence for a life or death assemblage since disarticulation into separated values occurs after the death of the organism. In contrast, brachiopods tend to close on death and are more commonly found articulated (i.e. having

dorsal and ventral valves still attached to each other). Fragmentation of fossils into broken pieces (bioclasts) suggests transportation, whilst preferred orientation of disarticulated values of bivalves implies deposition within a current. Evaluating such relationships often involves drawing fossils in situ together with their sedimentological context.

An example with in-situ fossils is given in Figure 10.5a and shows a layer containing abundant bivalves at the base of a Jurassic micritic limestone (lime-mud) bed from Sardinia. The bivalves appear in cross-section on a vertical rock face in a quarry and their state of preservation provides evidence on their transport and deposition.

The subject of the sketch is the bivalve-rich layer and, in particular, the cross-sectional shapes of the valves and their spatial relationships to each other. Some of the surrounding rock can also be drawn to place the layer in context, especially its position at the base of a curved bed. The curvature on a larger scale than the photograph is caused by hummocky bedding. Here there are two beds, with a lower bed that is thinner and poorly exposed, but also has bivalves concentrated at its base. To begin the drawing the spatial relationships need to be blocked-in with simplified lines. Rather than attempting to draw individual bivalves at this stage, the upper limit of the bivalve-rich layer can be outlined as shown in Figure 10.5b. This line will be removed in the final sketch but is useful to delimit the area in which the bivalves will be drawn.

The next stage is to add detail. Some fractures and a thin-laminated layer are useful to add first since these can be used to help position the bivalve shells. Drawing the bivalves is laborious owing to the large number of shells. A useful tactic in drawing such complex features is to choose a characteristic shell, which is easy to distinguish from others, and expand outwards, adding one shell at a time. Each bivalve shell can be simplified to curved lines with emphasis on whether the shell is articulated, disarticulated, or is a fragment of a single shell. Most here are disarticulated single valves with ~10 per cent present as articulated closed shells and sparse broken pieces. Whilst drawing the valves it is often necessary to erase several that have already been drawn and reposition them to ensure their spatial relationships are faithfully recorded. It is not necessary to rigorously keep to the initial drawing area, once sufficient numbers of shells have been drawn, the area can be amended, as shown in Figure 10.5c.

The last drawing task is to include the detailed features of the main subject (Figure 10.6). In this case the valves are decorated with 1–2 mm

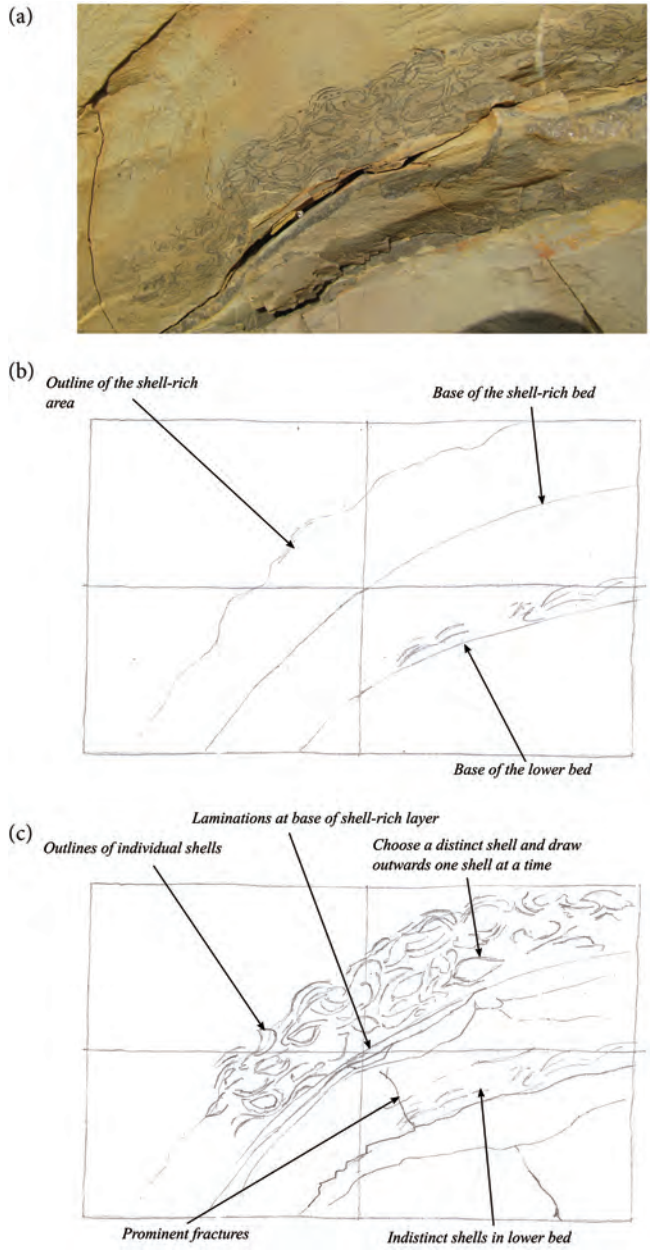
(a)
(b)
Outline of the shell-rich area
Base of the shell-rich bed
Base of the lower bed
(c)
Laminations at base of shell-rich layer
Outlines of individual shells
Choose a distinct shell and draw outwards one shell at a time
Prominent fractures
Indistinct shells in lower bed

Figure 10.5 Initial stages of a sketch of a bivalve lag from Jurassic limestones in Sardinia.

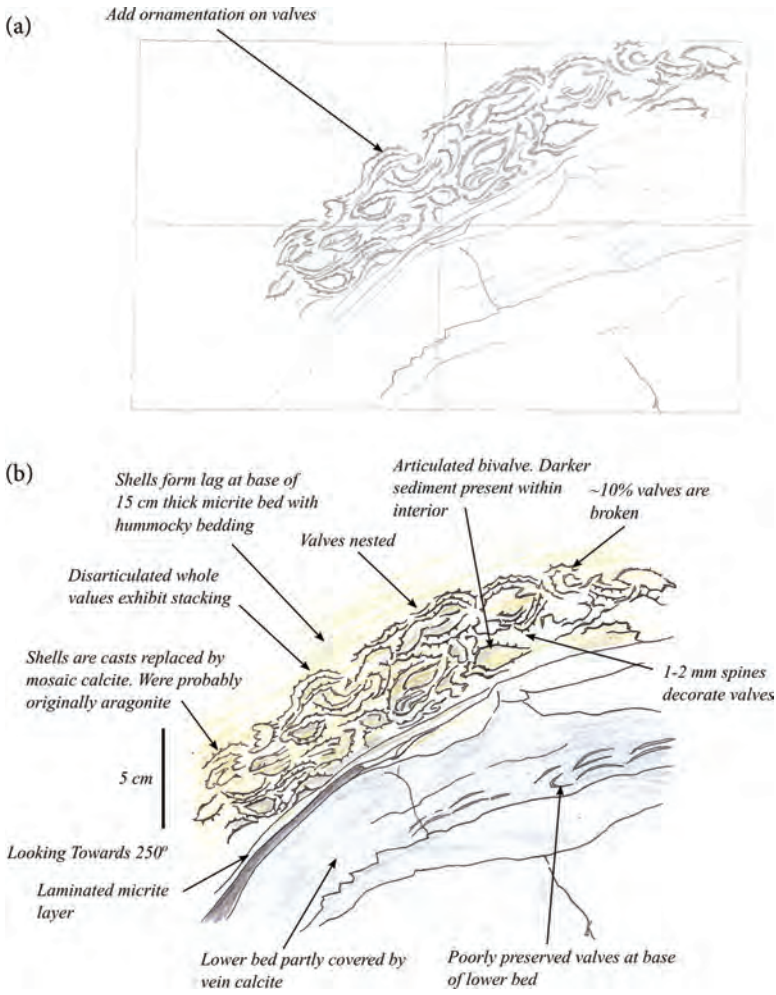
(a)
Add ornamentation on valves
(b)
Shells form lag at base of 15 cm thick micrite bed with hummocky bedding
Articulated bivalve. Darker sediment present within interior
~10% valves are broken
Valves nested
Disarticulated whole values exhibit stacking
Shells are casts replaced by mosaic calcite. Were probably originally aragonite
1-2 mm spines decorate valves
5 cm
Looking Towards 250°
Laminated micrite layer
Lower bed partly covered by vein calcite
Poorly preserved valves at base of lower bed

Figure 10.6 The final stages of a sketch of a bivalve lag.

high ridges on both the upper and lower valves. All the shells have similar structures, suggesting they are all the same species.

Finally, scale, direction, and labels are added.to the diagram. Particularly important for interpretation is the spatial relationship between the shells. They are nested with valves arranged into a close-packed arrangement. In some areas the shells are also stacked in the same orientation. Both suggest deposition of shells with a current as a basal lag on a packet of sediment emplaced quickly. The occurrence of some

articulated bivalves also suggests rapid transport and deposition within a single event since bivalves are held closed by adductor muscles and open upon death; furthermore, valves are partly attached by ligament and separate rapidly as they decay. The presence of some closed articulate bivalves suggests some were rapidly removed and transported whilst still alive. Once deposited the living bivalves were unable to escape the sediment layer, probably because they were epifaunal in nature (surface-living).

Also important to label is the sedimentological context. These lags are in beds with hummocky cross-stratification that is characteristic of shallow marine shelves with water depths between the fair-weather and storm wave base. The actual depths of these wave bases vary depending on the scale of the ocean basin, since surface waves are larger given greater reach. The depositional environment may suggest that the bivalves are being washed down slope from shallower water in storm-driven density currents.

Finally, the nature of the shells also has some significance. The presence of abundant thick ridges on the valves is potentially a defence adaptation to minimize predation, although it could also play a role in fixing the bivalve on the surface. Epifaunal bivalves in particular are most at risk from predation and the most likely to show thickened shells, ridges or the presence of spines. These bivalves are lower Jurassic in age; a time in which there was a dramatic increase in predation pressure owing to the diversification of predators. This had an impact on the evolution of prey organisms and is a period is known as the Mesozoic Marine Revolution.

10.4 Drawing ichnofossils

Trace fossils are important not just because they provide evidence by which depositional environment can be deduced but they also provide insights into the behaviour of organisms; even though the exact identity of the organism is often not known. An example of an interesting ichnofossil that is worthy of a sketch is given in Figure 10.7 and shows a burrow within the ammonite bed in the Lower Lias (Jurassic) of Lyme Regis. The image illustrates the navigation tactics of a burrowing organism within this heterogeneous sediment.

The most important features to record in this exposure are the morphology and state of preservation of the ammonite conches (shells), and the shape and size of the burrows present. During blocking-in of the

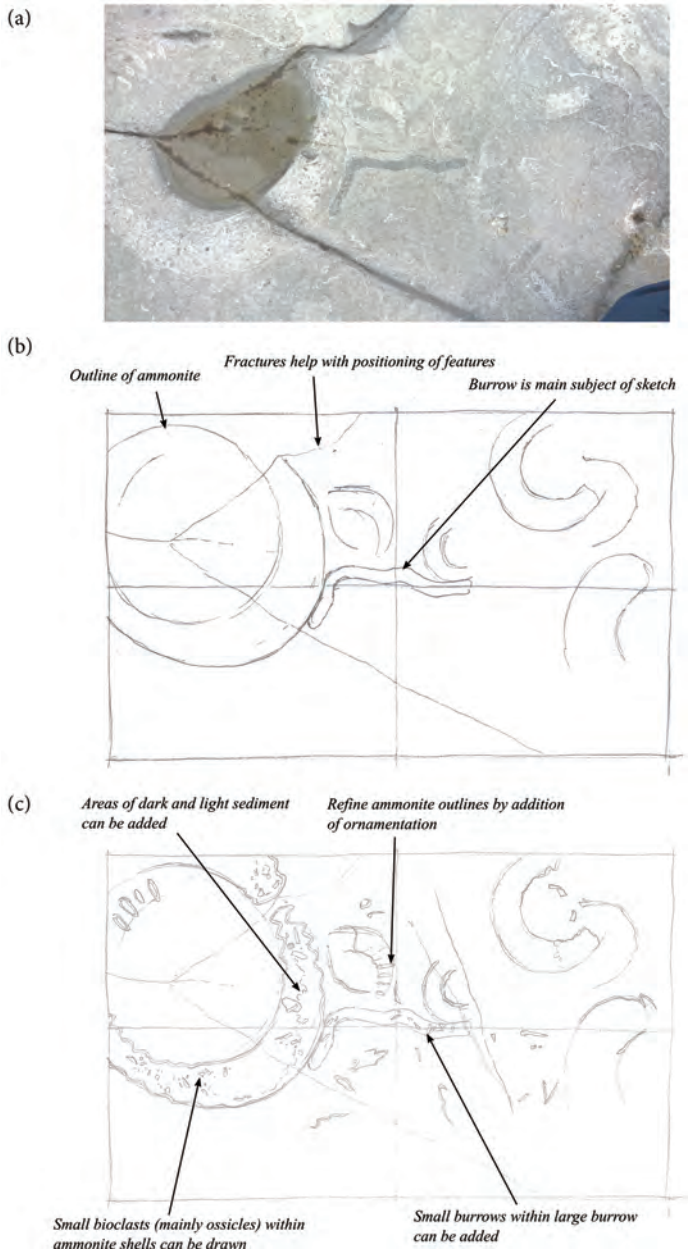
(a)
(b)
Outline of ammonite
Fractures help with positioning of features
Burrow is main subject of sketch
(c)
Areas of dark and light sediment can be added
Refine ammonite outlines by addition of ornamentation
Small bioclasts (mainly ossicles) within ammonite shells can be drawn
Small burrows within large burrow can be added

Figure 10.7 The initial stages of a sketch of a burrow in the ammonite bed at Lyme Regis.

sketch the trace of the ammonites on the surface can be drawn as simplified curves, paying particular attention to where the traces end at broken sections of the conch. The main subject of the sketch is the burrow, and this can be added using the ammonites to help position its features. The shape of the burrow, in particular its change in orientation are important to record accurately, as shown in Figure 10.7b.

There are many details that can be added to the sketch, which are important in the interpretation. Several ammonite conches show cross-sections through surface ridges including those on whorls below the surface of the bed indicating that the ridges are near rectiradiate. The size and shape of the ridges suggest the ammonites are *Arietites*—the largest Jurassic ammonites in the UK. The ammonite conches on the right of the photograph preserve only part of a single whorl and thus are broken. Details of the sediment filling the large conch on the left are also relevant since it contains abundant bioclasts, mainly of crinoid ossicles that are also present in the surrounding sediment. Darker limestone which may be more organic- or clay-rich also occurs in the right half of the whorl. There are some bioclasts within the limestone matrix between the ammonites that might be impressions of bivalves such as *Gryphaea*. Finally, the burrow, which is around 1.5 cm wide, contains abundant smaller tubular burrows several mm-wide. These details are added to the sketch in Figure 10.7.

The final stage of preparation is to add scale, orientation, and labels, as shown in Figure 10.8. Important features to label are those that illustrate

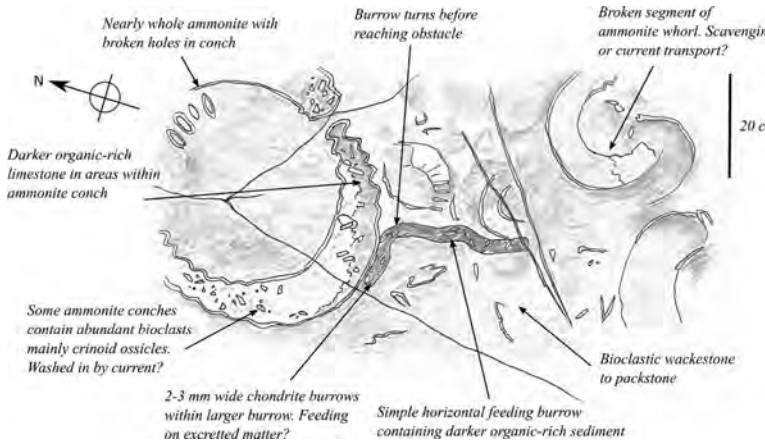
Nearly whole ammonite with broken holes in conch
Burrow turns before reaching obstacle
Broken segment of ammonite whorl. Scavenging or current transport?
N
20 cm
Darker organic-rich limestone in areas within ammonite conch
Some ammonite conches contain abundant bioclasts mainly crinoid ossicles. Washed in by current?
Bioclastic wackestone to packstone
2-3 mm wide chondrite burrows within larger burrow. Feeding on excretted matter?
Simple horizontal feeding burrow containing darker organic-rich sediment

Figure 10.8 Finished sketch of a burrow in the ammonite bed at Lyme Regis.

the identity of the fossils and depositional environment. Ammonites are pelagic organisms and thus they accumulate in this layer by settling to the seafloor after death. The large number of ammonite conches in this bed is anomalous. Concentration by currents after death can probably be discounted since a significant number of conches are nearly whole. Accumulation whilst still alive, for example by currents, followed by mass mortality, thus seems more likely. *Arietites* have low keels that give hydrodynamic stability and thus were probably active swimmers that are less easy to concentrate within currents than planktonic organisms. Ammonites like *Arietites* with open whorls (evolute ammonites), however, are unlikely to have been able to swim quickly owing to their hydrodynamic drag and thus concentration by strong storm-generated currents is possible. The lack of current-related sedimentary structures in this bed, however, isn't consistent with such a mechanism. Alternatively, the ammonites could have collected in this area to spawn where they were killed by an event such as a temporary anoxia event. Broken ammonite shells might also suggest predation by marine reptiles, for example, those attracted by the spawning event, but could also occur post mortem on the sea-floor by scavenging. Certainly, the assemblage of crinoids, bivalves and gastropods within the bed suggests a significant benthic fauna on an oxygenated sea-floor.

The main subject of the sketch is the burrow. The size of the burrow suggests it is *Thalassinoides*, despite the absence of T-junctions in this exposure. *Thalassinoides* are often formed as the feeding burrows of crustaceans. The burrow is infilled by darker sediment presumably indicating penetration and mixing of sediment from the underlying or overlying marl layers. A particularly interesting aspect of the burrow is that it begins to turn before reaching the ammonite conch and then skirts its margin for a distance. The organism was able to detect the barrier formed by the conch through 1 cm of sediment. The burrow once infilled was then bioturbated by thin *Chondrites* burrows, likely formed by worms. The combination of *Thalassinoides* and *Chondrites* suggests the *Cruziana* ichofacies associated with shallow marine environments.

10.5 Taxonomy diagrams

It is not common to draw fossils within the field to record taxonomy since specimens can usually be collected, however, studies that focus on palaeontology can involve drawing fossils where features are difficult

to capture in photographs. The key to such sketches is to faithfully record both geometry and detail on a range of scales. Geometry requires careful blocking-in during the initial phase of the sketch, since the outlines will guide the addition of later detail. Often this will involve repositioning lines and frequent use of an eraser. Drawing detail that is small in comparison to the overall fossil is best achieved using smaller satellite sketches that are connected to the main drawing.

An example of a taxonomical sketch is given in Figure 10.9 and shows a specimen of a Devonian brachiopod *Mucrospirifer* viewed from several different directions. Often it is necessary when drawing taxonomy to include several different views of a specimen to sufficiently illustrate the morphological features. In this case the symmetry of the valves, hinge and pedicle structure, and nature of the commissure, sulcus, and surface ornamentation are all important to include.

Blocking-in the drawing accurately is crucial in this sketch since the initial outline of the specimen will guide the placement of the smaller-scale features. Any errors in the initial geometry will distort the spatial relationships when it comes to adding features such as ribs and growth-lines. Rather than use a quadrant system to guide the initial outline, vertical and horizontal axes can be used and distances along each axis estimated. Choosing axes that lie along planes of symmetry will help ensure the drawing is accurate, as shown in Figure 10.9b. Straight-line segments can be drawn initially for the outline and can be erased and repositioned until they are correct. Further accuracy can then be added by refining these initial lines as curves, as shown in Figure 10.9c. Particular attention should be paid to accurate geometry since the quasi-regular shapes of many fossils can lead to a tendency for schematic diagrams that reflect expectation rather than observation. In the current case the brachiopod has a high degree of symmetry but there are some divergences from a perfectly symmetrical shape. Some additional details such as the sulcus and commissure can also be included at this stage.

In this sketch the ribs on the surface of the valves are prominent detailed features and their placement greatly influences the accuracy of the drawing. A useful tactic in drawing a series of self-similar features whose position is critical is to count the number of features that intersect with another line, such as the commissure (the line along which the brachiopod gapes). Here the width of the ribs decreases outwards from the sulcus (the indent in the centre of the dorsal valve). Each rib

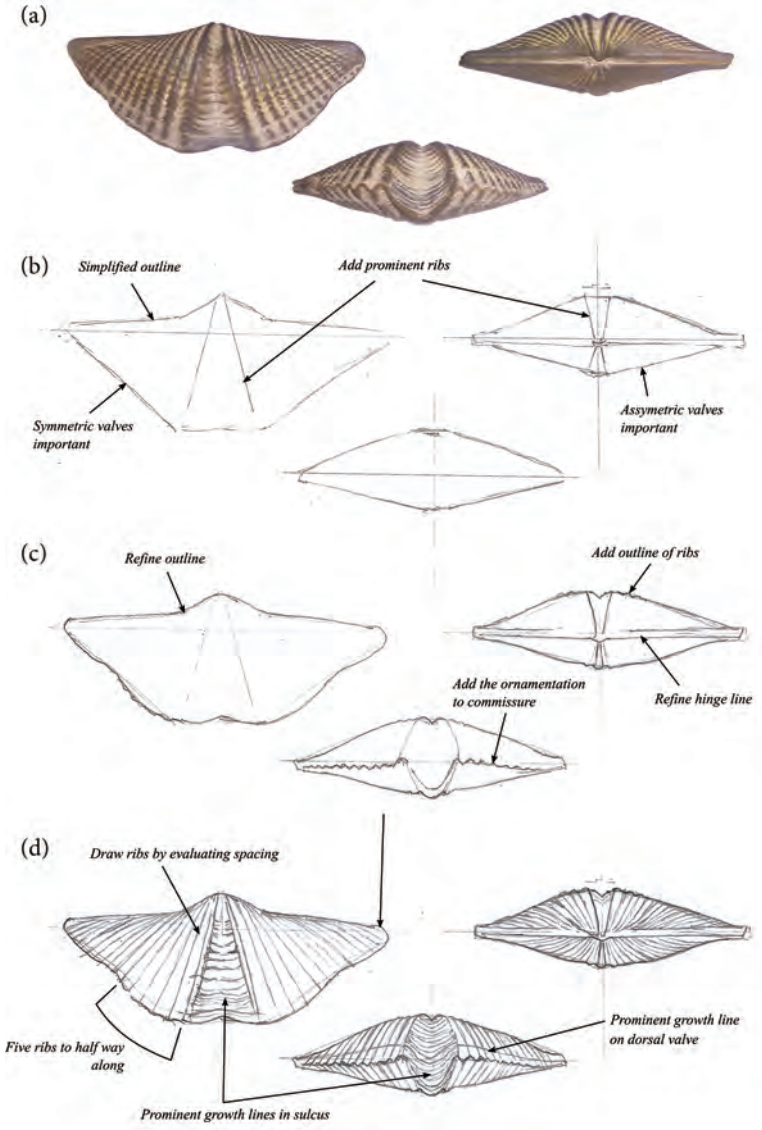

Figure 10.9 Stages in a taxonomy drawing of the brachiopod Mucrospirifer.

connects the commissure with the pedicle as a nearly straight line. Counting the number of ribs outwards from the sulcus gives five ribs to halfway along the commissure, then another five ribs to three quarters of the way along the commissure. Adding the ribs using such a scaling method ensures there spacing is correct, as shown in Figure 10.9d. Some other pronounced features can also be added at this time, such as the prominent growth-lines in the sulcus.

The final lines to be added will denote the subtler features. The growth-lines on the valves either side of the sulcus are less prominent than the ribs and most easily seen towards the commissure and close to the centre of the valve where they have a cuspate shape. The growth-lines can be added as somewhat discontinuous lines by paying attention to their spacing, as shown in Figure 10.10a. Where they connect to the hinge is also important to record accurately since this relates to the shape of the brachiopod at an earlier stage of development.

The last task with this drawing is to add a scale and labels. All morphological features should be labelled with proper terminology. Some

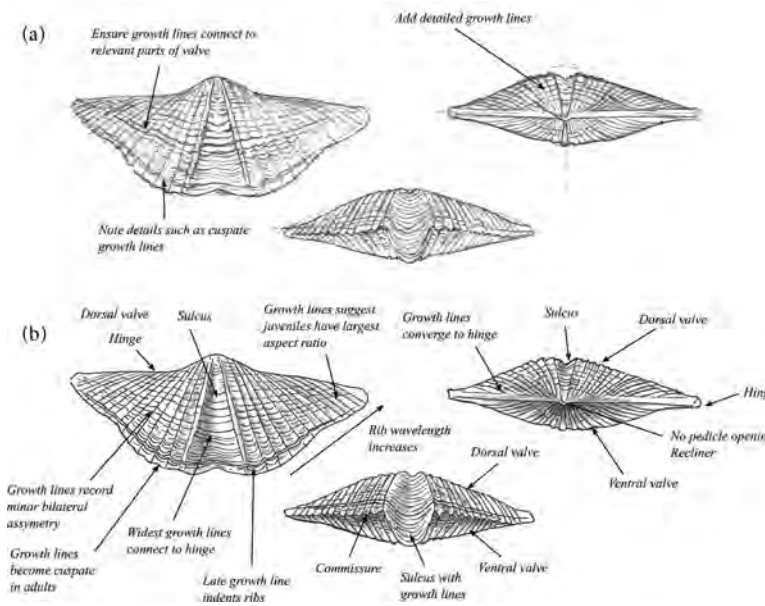

Figure 10.10 Final stages in a taxonomy drawing of the brachiopod Mucrospirifer.

interpretation can also be added where appropriate. In this case the growth-lines show that lateral growth occurs rapidly at an early stage followed by growth perpendicular to the commissure, with little further extension laterally. The widest growth-lines correspond to the stage at which growth switches. Shading is also a useful addition to taxonomy drawings to give the impression of volume; however, it should not obscure the morphological details. Colour is a good way to add shading, but stipples have often been used instead in palaeontology textbooks but are laborious to produce.

10.6 Other examples

Several examples of sketches of fossils from the author's field notebooks are shown in Figure 10.11 and illustrate differing styles depending on objective. The sketches in Figure 10.11a and f show the taxonomy of brittle-stars from the Jurassic Solnhofen limestone in Germany and goniatites from Devonian limestones in Morocco. Both sketches were undertaken to record the taxonomy of the fossils as an *aid memoire* for comparison to other specimens. The drawings were quick recordings without significant additional detail incorporated. The sketch in Figure 10.11f shows rudist bivalves from Cretaceous limestones in Aliaga in Spain. The objective of the sketch was to illustrate the interrelationships between the valves of adjacent bivalves within a closely packed patch reef—it thus records the life-position of the fossils as well as taxonomy. Figures 10.11b and d show stromatolites from a 2.7 billion year old limestone in the Pilbara of Australia. These sketches were drawn to illustrate both the morphology of the stromatolite domes and their relationship with the surrounding sediment. In Figure 10.11d, micritic limestones with ripple marks are recorded forming channels through the stromatolite reef. The stromatolite domes were observed to be elongate in the current direction. Finally, Figure 10.11c shows a horseshoe crab fossil from the Solnhofen limestone of Germany. This fossil was on display in the Solnhofen museum, but the display cabinet prevented photography. The specimen was drawn to illustrate the tool marks associated with the fossil that suggest the crab was attempting to escape from anoxic water at the base of the water column. The marks either side of the telson may record the death spasms of the crab.

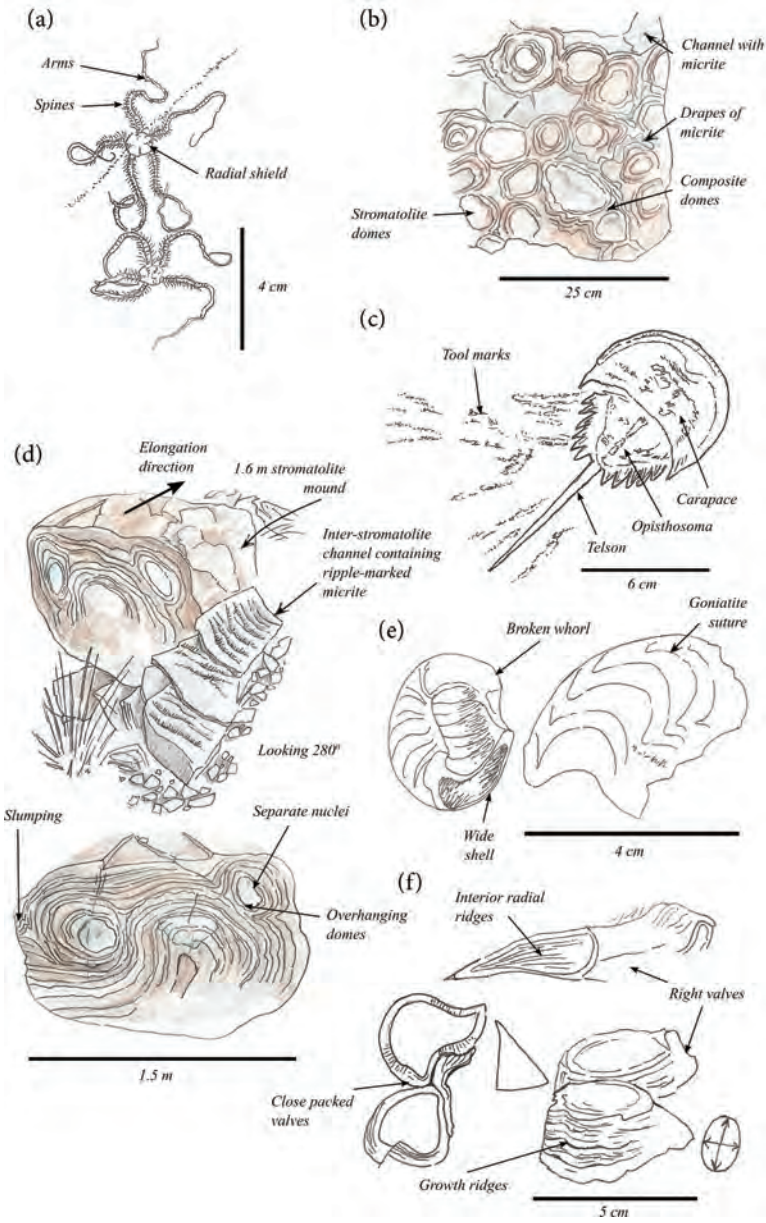

Figure 10.11 Examples of sketches of fossils from the author's field notebooks.

10.7 Key concepts

In this chapter, several key concepts and methods were introduced:

- Drawing fossils is most useful when recording their sedimentological context or mode of life.
- Blocking-in sketches accurately is particularly important when drawing fossils since their quasi-regular shapes can lead to drawings that are overly schematic.
- Small-scale morphological features are often important in the interpretation of fossils.
- The state of preservation of fossils should be recorded in a sketch since this has implications for their degree of transport or the occurrence of predation and scavenging.

11

Drawing hand-specimens of rocks and crystals

Whether hand-specimens should be drawn in the field depends on the time available. Hand-specimens can be collected and can often be photographed even in difficult light conditions by the simple artefact of moving them into the shade. Those specimens that show particularly important features, with interpretations that are crucially important, could, however, be drawn. An example is where differences in petrology uniquely define mappable units with an area, such as lava flows with different textures. These can be considered the type specimens for the area of study. Specimens that define a process not observable in situ are also worthy of drawing. Conversely, those specimens with no visible features, such a massive mudstones or siltstones, are almost certainly not worth sketching.

Any higher magnification sketch of a small area of rock, whether in situ or not, is essentially a hand-specimen image. Often these are useful to arrange as peripheral drawings around an outcrop-scale sketch since they provide enhanced resolution and detail. The crucial element to drawing hand-specimens is the ability to simplify the petrology whilst maintaining an adequate level of detail. Being able to identify what are the most important features to draw in a hand-specimen requires skills in mineral and rock type identification.

11.1 Identifying minerals

Mineral identification in hand-specimens involves evaluating those properties of a mineral that can be observed or tested to determine the most likely identity. Usually it is not possible to determine all the properties of a mineral, for example, crystals are often anhedral (show no characteristic faces) or subhedral (show only some of their characteristic faces), making it difficult or impossible to evaluate their crystal system.

Geological Field Sketches and Illustrations: A Practical Guide. Matthew J. Genge, Oxford University Press (2020).
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Small crystals can also make it difficult to observe cleavage (planar fractures) or to test physical properties such as density, hardness, and streak. Most of the time, therefore, only a few properties are available in order to identify a mineral and as a result there will usually be a degree of uncertainty in their identification.

A useful tactic in mineral identification is to know what minerals to expect within different types of rock, since it is then only necessary to be able to distinguish between those minerals that are commonly found together. Often it is the abundant rock-forming minerals that are used in defining rock types and are thus of the most significance.

In light-coloured (leucocratic) rocks quartz and feldspar are the commonest felsic minerals. Both can be similar in colour or transparent, however, quartz can easily be distinguished from feldspar by its lack of cleavage and the presence of shell-like conchoidal fractures. If large enough to perform a hardness test, quartz is harder than feldspar and quite often has a vitreous lustre. In clastic sedimentary rocks such as sandstones and conglomerates quartz and feldspar are also the commonest grains. In sandstones the small size of grains often makes cleavage difficult to see. However, feldspar weathers much more easily than quartz, leading to chalky white grains, whilst quartz remains vitreous.

Calcite can also be found with quartz in clastic rocks, either as single crystals or as limestone lithic grains. Both calcite and quartz are also common within veins. Distinguishing between the two minerals can be achieved easily since calcite usually has a well-developed rhombohedral cleavage and reacts with dilute hydrochloric acid.

Distinguishing between plagioclase and alkali feldspar is difficult. In light-coloured igneous rocks, such as granites, both often occur together. When present as large crystals the polysynthetic twinning of plagioclase can be seen using a hand-lens on one of its two cleavage planes. When the alkali feldspar is perthite, lamellae can also frequently be seen on cleavage planes and crystals are most commonly pink in colour. In most mafic (dark) igneous rocks plagioclase is usually much more abundant than alkali feldspar.

Mafic minerals are relatively easy to distinguish from each other with the most common being micas, amphiboles, pyroxenes, and olivine. Micas are characterized by their perfect basal cleavage, which tends to split them into flakes, making them easy to identify. The micas biotite and muscovite are the most common and are often found together

in granites and in metamorphic rocks such as schists. Muscovite is the most abundant mica within phyllites. Mica also occurs as flakes in micaceous sandstones.

Amphiboles and pyroxenes often look similar but can be distinguished by the intersection angles of their cleavages. Pyroxenes have cleavages that intersect at 90° and amphiboles at 124°. Often the cleavages are best seen on a broken surface with pyroxene cleavages forming rectangular shapes with surfaces at right angles. When cleavage cannot be seen, amphiboles more commonly occur as elongate crystals than pyroxenes. Pyroxenes are usually more abundant in mafic igneous rocks than amphiboles.

Olivine can usually be recognized by its characteristic green colour and vitreous lustre and is common in both mafic and ultramafic igneous rocks. In ultramafic rocks, such as peridotite, however, olivine is often present together with pyroxenes that also can be green. Olivine and pyroxene can be distinguished by the lack of cleavage in olivine.

There are a great many less common minerals, which can be locally abundant within certain rock types. Worthy of mention are index minerals within metamorphic rocks. Within schists and gneisses these are garnet, staurolite, and kyanite. Garnets tend to occur as hard equant (equal dimensions in every direction) crystals and are thus easy to identify, even if they are highly variable in colour. Kyanite and staurolite occur as elongate crystals, where kyanite has a bladed habit and staurolite commonly exhibits cruciform (crossed) twins.

Every geologist should be able to identify all the minerals discussed above together with the most abundant ore minerals, such as pyrite, chalcopyrite, galena, sphalerite, and hematite, and evaporates, such as gypsum and halite. More information on how to identify minerals can be found in a good mineralogy textbook, such as *Introduction to Mineralogy* by William Ness.

11.2 Identifying rock types

The first step in identifying rocks is to determine whether the specimen is metamorphic, igneous, or sedimentary. These three groups can be easily distinguished at a simplified level on the basis of texture and fabric. Most sedimentary rocks consist chiefly of clasts and grains of preexisting rocks and minerals, whilst most igneous rocks mostly consist of interlocking crystals and/or glass (i.e. they are crystalline), and most

metamorphic rocks are crystalline materials in which minerals have a preferred orientation to create a fabric.

There are, however, numerous exceptions to these simple guidelines. Sedimentary rocks, for example, include some that are crystalline, such as evaporates and some limestones. Not all clastic rocks are sedimentary either. Pyroclastic rocks are igneous materials formed by fragmentation during explosive volcanic eruptions and mainly consist of clasts of igneous rock (see Section 8.4 for their lithologies). Cataclasites and fault breccias are likewise clastic but are formed by dynamic metamorphism. Finally, metamorphic rocks formed by thermal metamorphism are crystalline, but can lack a foliation. All these exceptions must be considered when identifying rocks and sometimes leads to uncertainty.

Once the rock group has been identified, determining the rock type is relatively simple, at least for most common types. Igneous rocks are classified by mineral abundances and grain size, as shown in Figure 11.1 where only the essential minerals quartz-plagioclase-alkali feldspar and feldspathoids (e.g. nepheline and leucite) are used to give a rock name for acid, intermediate, and basic rocks. Mafic minerals, however, will also be present, as illustrated in the diagram. Although this classification system is relatively simple, there are some complications. Silica-rich fine-grained igneous rocks, such as dacite and rhyolite, are often glassy and their mineral abundances will be different to those in the classification diagram. Rhyolites in particular are frequently glassy and banded. Medium-grained rocks (average crystal size 1–3 mm) are usually given the same name as their coarse-grained equivalent with the prefix 'micro-'. Dolerite, however, is used for a medium-grained basic rock rather than micro-gabbro. There are also a large number of variants and sub-types of igneous rock, as well as a few unusual rock types such as kimberlite, that are not easily included in the classification system.

The textures of igneous rocks are not important in identifying rock type, but are crucial in the interpretation of their mode of formation. Fine-grained igneous rocks are mostly formed as lavas or shallow intrusions and usually contain larger crystals (>1 mm) within a fine-grained (aphantic) groundmass. The larger crystals are known as phenocrysts and usually form during prolonged cooling at depth. The texture of igneous rocks containing larger crystals within a finer-grained groundmass is termed porphyritic. Those fine-grained rocks that lack phenocrysts have

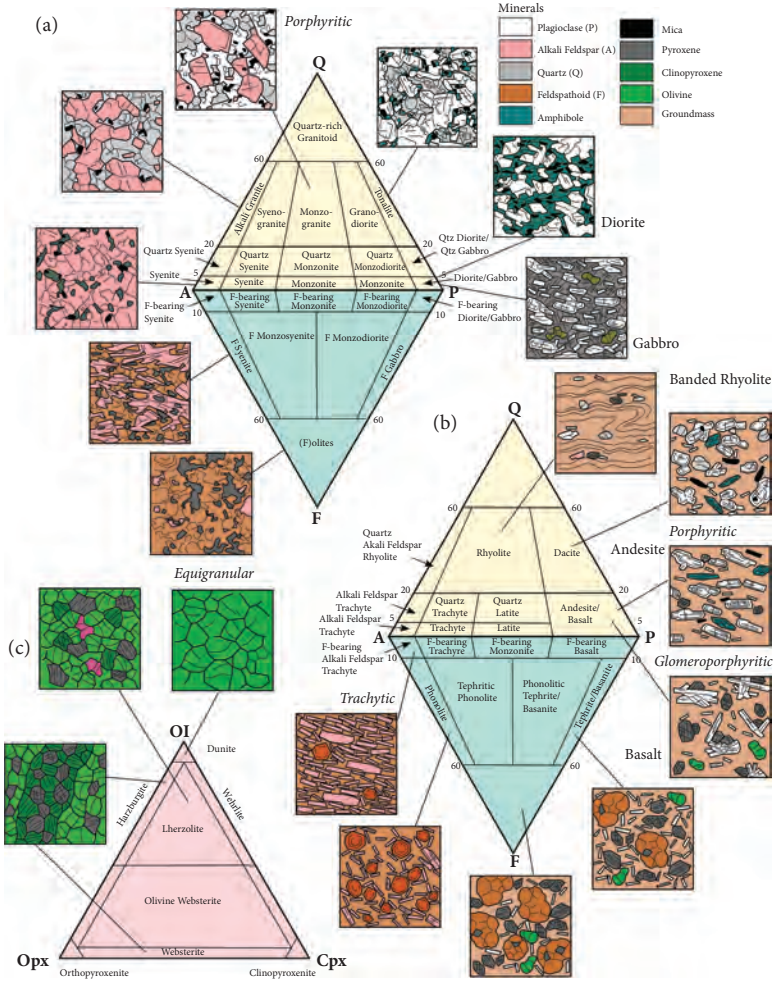

Figure 11.1 The classification of igneous rocks. Some examples of texture are also given but are not specific to particular rock types. Pictures are labelled with texture names in italics.

apyric textures. Most coarse- and medium-grained igneous rocks have equigranular textures, however, some are porphyritic. Examples of textures are illustrated in Figure 11.1.

Sedimentary rock classification differs between siliciclastic rocks (silicate-dominated) and limestones (carbonate-dominated). Siliciclastic

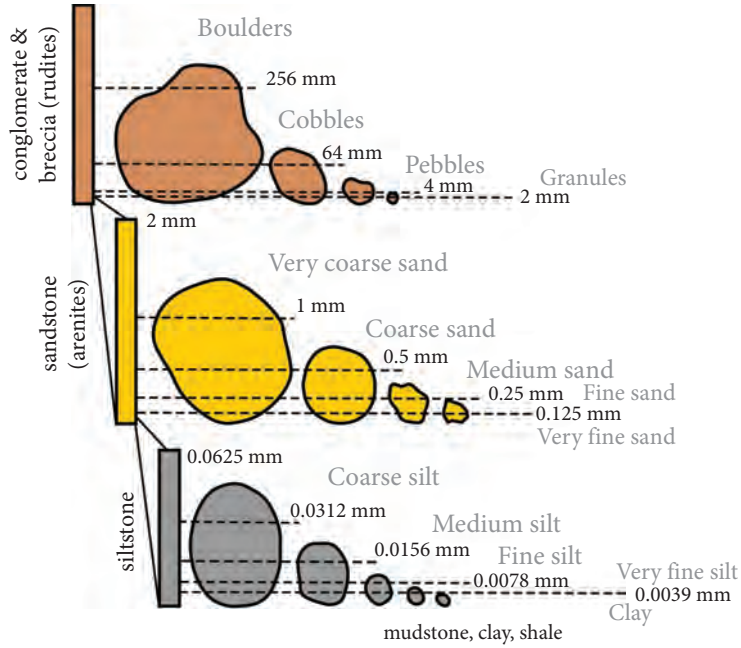

Figure 11.2 The classification of clastic igneous rocks by grain-size.

rock classification is shown in Figure 11.2 and varies according to grain size and composition. Most sandstones are dominated by quartz, feldspar, and lithic grains producing the varieties quartz arenite, arkose, and litharenite, respectively. Sandstones containing mud are described as greywackes when they contain >15 vol per cent clay, and argillaceous sandstones when they contain 5–10 vol per cent. Sandstones containing carbonate are termed calcareous sandstones.

There are two main classification systems used for limestones, the Folk and Dunham classifications. The Dunham classification, which is used more widely and is shown in Figure 11.3, depends on the abundance of grains, matrix, and cement. An important aspect of limestone lithologies is the nature of grains, known as allochems, which can be ooliths, peloids (pellets), pisoliths, or bioclasts (fossil fragments). These terms can be used as a descriptive prefix to the Dunham classification if one type of grain dominates, as shown in Figure 11.3.

Metamorphic rocks can be subdivided into regional, dynamic, and contact metamorphic rocks. Regional metamorphic rocks formed from

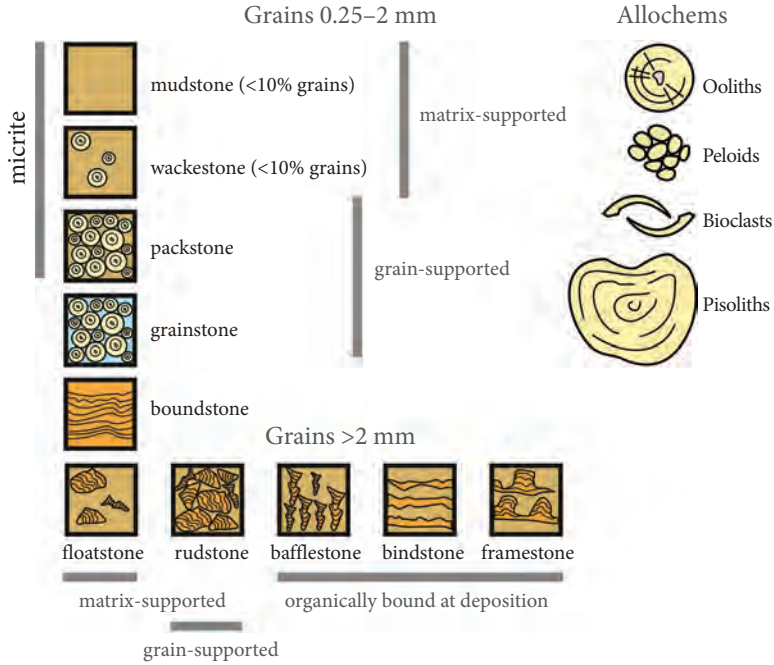

Figure 11.3 The Dunham classification of limestones.

by metamorphism of mud rocks include slate, phyllite, schist, and gneiss. These rocks have fabrics and foliations and were described in Section 5.1.1. Contact metamorphic rocks can lack fabrics and have crystalline textures and are known as hornfels. Dynamic metamorphic rocks form as a result of shearing or brittle failure to produce fault rocks such as fault gouges and breccias, cataclasites, or foliated mylonites.

11.3 Drawing hand-specimens of rocks

Often hand-specimens worth drawing have unusual features that illustrate a specific process or have lithological properties that make them unique within a study area. The common feature of all hand-specimens, however, is that they are small with an outer surface. This feature, although usually the least important, is crucial to drawing well since it can be used as a guide to positioning other elements within the sketch.

11.3.1 Pillow lava

A sketch of a broken piece of a pillow lava from Iceland is shown in Figure 11.4. This specimen has a glassy chilled rim on the right, green euhedral (well-shaped) crystals of olivine concentrated on one side, and a central gabbroic xenolith. There are, therefore, plenty of features in this specimen to make drawing it worthwhile.

The process of drawing the sample involves choosing its orientation to best show the features of interest, then drawing a simplified outline

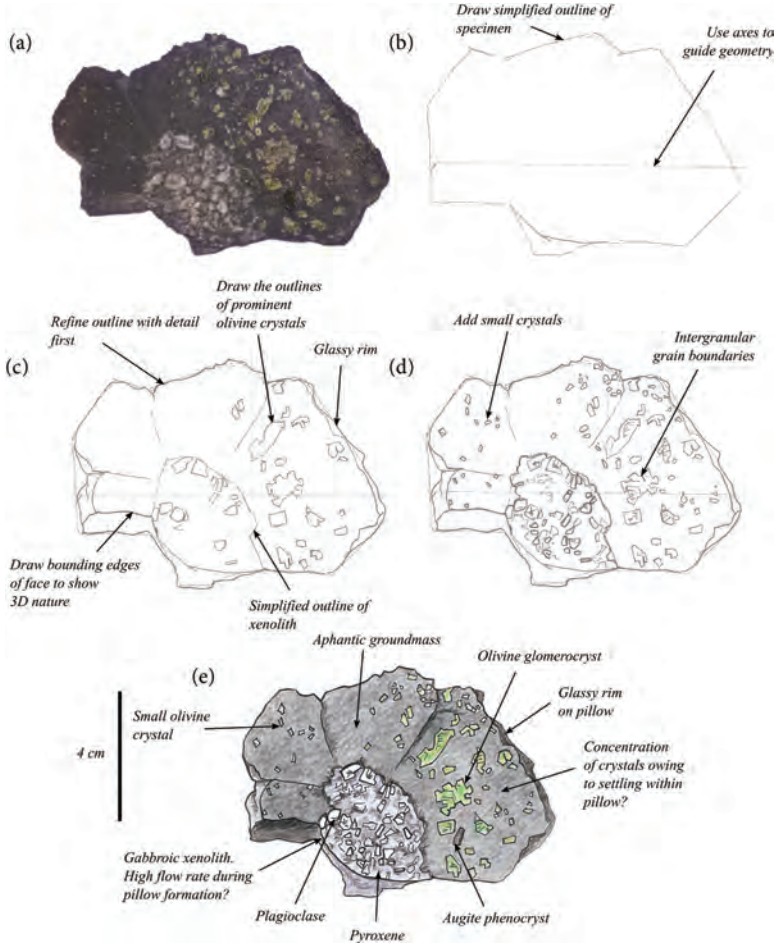

Figure 11.4 Sketch of a broken pillow lava.

of the specimen. The shape of the outline can be defined using axes instead of a quadrant grid, where positions are determined by the relative position of corners. Drawing the outline as straight-line segments makes it easier to reposition lines until they are correct. Detail can then be added, starting by refining the outline with minor protrusions and indents.

Next, the most important internal features can be drawn by first recording their outlines. The specimen contains a gabbroic xenolith and contains olivines in clusters of crystals known as glomerocrysts. The xenolith is broadly elliptical with a couple of indents. The olivine glomerocrysts have re-entrant outlines. Every glomerocryst need not be drawn, only enough to adequately illustrate the texture. Finally, there is also a glassy rim on the right edge of the sample that marks the exterior of the pillow.

Additional details can then be added. Crystals of plagioclase are present within the gabbroic xenolith and have broadly rectangular (lath-like) outlines. The larger crystals can be drawn together with some of their internal details, such as cores with slightly different colour—suggesting these are zoned crystals. Between the plagioclase crystals are darker pyroxenes but little of their crystal shapes can be seen. Some lines can be added to indicate the most obvious crystal boundaries and give the xenolith a granular texture. Likewise, some inter-grain boundaries within the glomerocrysts can be drawn to illustrate that these are clusters of crystals.

Hand-specimen sketches do not require a looking towards direction, unless they are a higher magnification drawing of an in-situ specimen, however, they do require a scale and labels. Colour is useful in this diagram to illustrate mineralogy. It is always necessary to add descriptive labels giving mineralogy and textural terms. Labels are also useful in recording the interpretations made during drawing. There will always be some interpretation if a specimen was worth drawing. Here the glassy rim relates to rapid cooling of the magma by water, in this case within a sub-glacial lake generated by the heat of the magma. The concentration of the olivine crystals on one side of the pillow is also interesting since it is likely to have been produced by settling of these dense minerals within the melt. Settling within pillows is unusual and might originate if this pillow acted as a conduit for flow of magma into adjacent pillows. Likewise, the gabbroic xenolith implies sufficient flow to transport larger clasts.

11.3.2 Hydrothermal veins

A second example of a hand-specimen drawing is given in Figure 11.5, which shows a network of hydrothermal veins containing sphalerite (ZnS) within a phyllite host rock. Veins are often worth drawing when their spatial relationships allow interpretation of the nature and evolution of mineralizing fluids. Here the geometrical relationships between the veins and the position of the minerals are important.

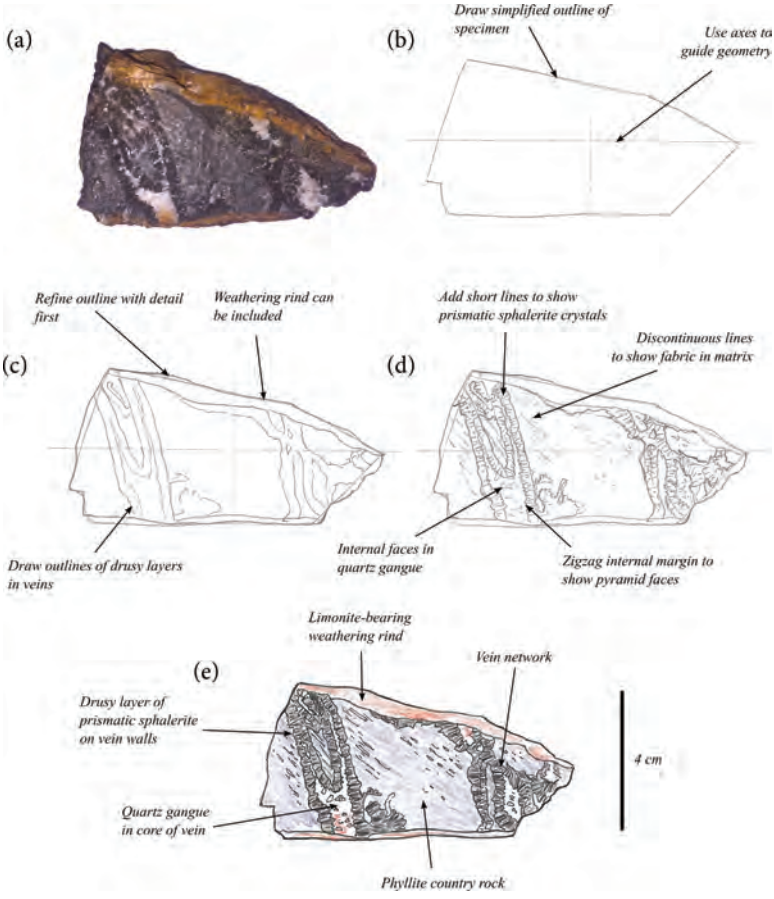
(a)
(b)
Draw simplified outline of specimen
Use axes to guide geometry
(c)
Refine outline with detail first
Weathering rind can be included
Draw outlines of drusy layers in veins
(d)
Add short lines to show prismatic sphalerite crystals
Discontinuous lines to show fabric in matrix
Internal faces in quartz gangue
Zigzag internal margin to show pyramid faces
(e)
Limonite-bearing weathering rind
Vein network
Drusy layer of prismatic sphalerite on vein walls
Quartz gangue in core of vein
Phyllite country rock
4 cm

Figure 11.5 Hand-specimen of hydrothermal veins within phyllite from Argentiera silver mine in Sardinia.

In this sketch the veins are best positioned using the outline of the hand-specimen. On the left, for example, a vein trends from the upper left corner of the specimen to approximately one quarter the way long the bottom surface—it bifurcates into two thinner veins approximately one-third of the way along its length. The vein can initially be outlined to position it accurately; then the outline of the dark sphalerite layer can be added as this feature is prominent and easy to see.

There are several important details to be drawn in this sketch. Firstly, the sphalerite crystals are tabular and oriented nearly perpendicular to the margins of the vein. The sphalerite grew as a drusy layer directly onto the wall rock from the fluid filling the vein. The sphalerites are most easily drawn by adding straight lines to represent the boundaries between the crystals. Although such features are somewhat schematic, care should be taken to record variations in the width of crystals. The sphalerites have domal terminations where they meet the quartz gange producing a zigzag boundary. This too can be added semi-schematically, but ensuring that larger crystals penetrate slightly further into the gange in the centre of the vein. The quartz is also crystalline but the boundaries between individual crystals are difficult to see. Crystal faces can be drawn in this area where they are obvious and help indicate the grain size and the crystalline texture, as shown in Figure 11.5d.

Finally, there is a fabric in the host country rock resulting from the alignment of muscovite and chlorite crystals producing a cleavage. On the surface of the specimen this can be seen as a series of closely spaced cleavage traces, however, this is difficult to see in a photograph and most apparent when the specimen is moved around in the light. The cleavage can be drawn as a series of sub-parallel lines. The traces are indistinct, thus discontinuous lines are be used. It is important that the spacing and length of the lines is variable, since these structures are not regular.

Colour is important in this sketch to convey the different minerals present. Usually, only the base colour of minerals is possible to record. Although lustre is an important property of minerals, it produces spatial colour variations related to the quality of light reflection and is difficult to reproduce using the limited palette available in pencils. Finally, scale and labels need to be added. Here the labels focus on the occurrence of the minerals since the paragenesis is not obvious in this specimen. However, the presence of ore at the margins of the vein indicate that

the fluid was initially saturated in sphalerite and then became depleted as it crystallized.

11.3.3 Crystalline rocks

Coarse-grained crystalline rocks can be daunting to draw owing to the large number of crystals and boundaries present. Sedimentary rocks, such as breccias and conglomerates, and pyroclastic rocks, such as lapilli-tuffs, can likewise be difficult to draw owing their large number of grains. The tactic to use when drawing such specimens is to selectively simplify the texture. Only the largest crystals and those showing the most significant textural features can be drawn in full. The texture of smaller crystals must be implied by drawing enough to illustrate them. This method requires a careful initial observation to identify which features are important to record.

An example of a crystalline hand-specimen is given in Figure 11.6 and shows a porphyritic granite from Cornwall in the UK. Large lath-like phenocrysts of orthoclase with Carlsbad twins and thin, light-coloured outer zones are present. The groundmass consists of finer-grained orthoclase, plagioclase, quartz and biotite and has an equigranular texture. There is a slight concentration of biotite at the margins of some orthoclase phenocrysts.

The outline of the specimen is drawn first and used to help position the phenocrysts. These crystals are the most significant feature of the specimen to record. Initially their outlines are drawn in a simplified form then refined with detailed steps and indents. Internal detail is also important in these crystals. Some have twin planes and many exhibit visible cleavage, both can be drawn as simple lines. Cleavage planes have variable spacing and often cannot be followed all the way across crystals and thus are drawn as discontinuous straight lines. Care should be taken not to use schematic regularly spaced lines. Zones and trails of inclusions are also present in some of the orthoclase crystals. The zones can be drawn as discontinuous lines that are broadly parallel with the outer margins of the phenocrysts. Inclusions are small and thus drawn as speckles.

To record the texture of the groundmass the largest and most obvious crystals present can be outlined. Most of these are pale coloured orthoclase crystals. Their shapes and relative positions are important to draw. Some smaller crystals can also be included; however, their shapes can be simplified. Although there are hundreds of groundmass

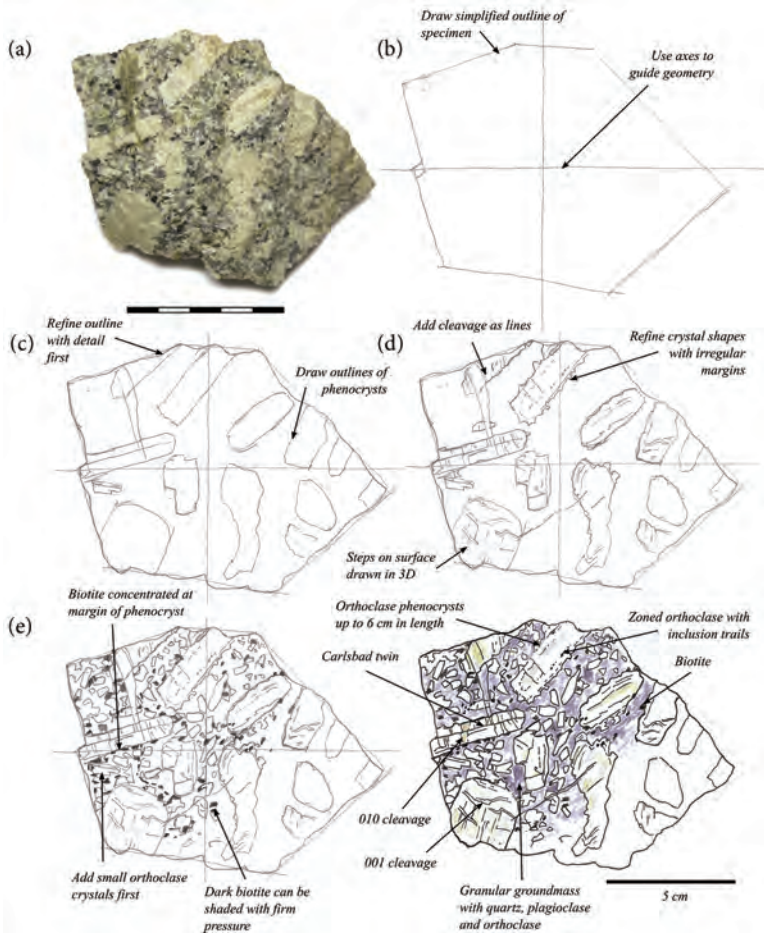

Figure 11.6 Hand-specimen drawing of a porphyritic granite from Cornwall in the UK.

orthoclase crystals present only ~30 were drawn, which seems to be enough to demonstrate the texture. The quartz and plagioclase are difficult to distinguish in the photograph, largely because they both appear grey and differ in the presence of cleavage in the plagioclase, whilst quartz has conchoidal fracture. Since these features are subtle and require a hand-lens to see, no attempt is made to draw them. Biotite crystals, however, are obvious. These can be quickly drawn by scribbling with

the pencil. Care is taken, however, to ensure their shapes and locations are broadly correct, as shown in Figure 11.6e.

Colour is essential in this drawing to allow the minerals to be distinguished. There are some colour variations in the orthoclase crystals that allow chemical zones to be highlighted. Colour is particularly useful to give and impression of the texture in the groundmass. Transparent quartz here appears darker grey than plagioclase. Colouring the grey areas of the groundmass, paying attention to where the colour is darker, thus produces a much more realistic and valuable sketch. Finally, labels and scale are added.

11.4 Drawing crystals

Counterintuitively, the regular forms of crystals make them challenging to draw realistically. Firstly, although crystals exhibit specific symmetries, namely cubic, tetragonal, orthorhombic, monoclinic, triclinic, trigonal, and hexagonal, their development of minor faces varies from crystal to crystal; thus the actual shapes of crystals vary considerably. The growth of crystals is also often imperfect with some faces poorly developed and broken surfaces present. Crystals are often, therefore, not as regular as expected, and there is a tendency to draw what is expected rather than what is seen. Next, crystals exhibit a wide variety of habits, such as acicular, bladed, tabular, and botryoidal, which make their forms even more variable. Crystals also exhibit properties such as transparency and lustre that are challenging to record in a sketch since they produce complex differences in shade. Finally, minerals are often found as part of an assemblage of many crystals meaning a high level of detail is present. Drawing crystals is most useful when this spatial context is also recorded.

An example of the drawing of a crystal is given in Figure 11.7 and shows two singly terminated quartz prisms that exhibit parallel growth. Like all hand-specimen images the outline of a sample provides a guide for further development of the sketch; allowing the positioning of more detailed elements. A particularly important feature is the stepped boundary between the two crystals that relates to their simultaneous mutual growth. Once individual crystals and the boundaries between them have been drawn then details such as cleavage planes and growth striations can be added. Often these features are less pronounced and can be drawn as discontinuous thin lines.

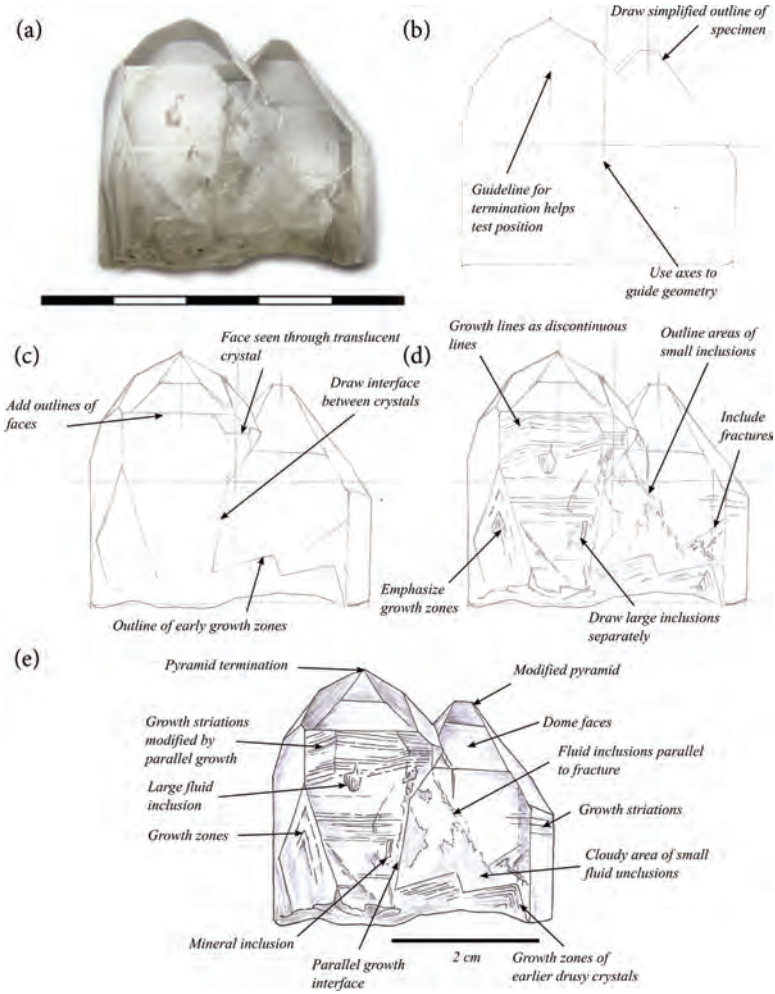

Figure 11.7 Hand-specimen drawing of crystals of quartz exhibiting parallel growth.

In this specimen some additional features can be seen. Fluid inclusions are present as large individuals and as areas of abundant microscopic inclusions, which give regions of the crystals a cloudy appearance. The outlines and some of the interior detail of larger inclusions can be seen and drawn; however, the cloudy areas can only be outlined with discontinuous irregular lines. The shapes of these areas can, however,

be important. Just to the right of centre in this crystal, a linear cloudy zone appears and is likely to represent where a fluid penetrated along a fracture. Healing of the crystal (by continued growth) sealed the fracture and trapped fluid inclusions.

Close observation of the crystal whilst drawing reveals some regular structures at the base of the specimen. On the left, exposed on one face, are growth zones that relate to the prismatic shapes. Small fluid inclusions help the growth zones to be seen. At the base of the specimen on the right are growth zones that appear as steps. These suggest an earlier stage in crystal growth, presumably as a drusy layer on a substrate. Inclusions and growth zones will appear emphasized in the final sketch compared with photograph; however, recording subtle but important features is the objective of drawing.

Colour is important when drawing crystals since, although not particularly characteristic of particular minerals, it is a fundamental and obvious property. The issue with most crystals is that transparency and the reflection of light (lustre) change the colours observed. Drawing realistic pictures of crystals, however, involves attempting to reproduce some of these colour variations by taking note of where the crystal is lighter and darker, as shown in Figure 11.7e. Finally, labels and a scale are added to the sketch.

11.5 Common mistakes

11.5.1 Idealized crystals

Drawing idealized crystal shapes that exhibit perfect crystal symmetry is a common mistake in drawing individual crystals and vein specimens, as shown in Figure 11.8. Crystals always have some faces that are better developed than others and usually have features such as growth striations, fractures, and inclusions that mean they diverge from their ideal geometries.

11.5.2 Insufficient detail

The commonest mistake in drawing hand-specimens is to oversimplify the petrology with a result that there is insufficient detail to illustrate the texture. An example of a hand-specimen sketch with too little detail is shown in Figure 11.9. Such diagrams have little value and are not worth the time spent in their production.

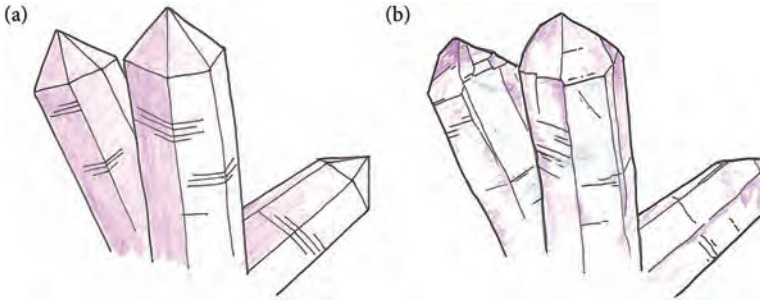

Figure 11.8 Showing two drawing of the same specimen of amethyst. In the drawing in (a) an idealized hexagonal geometry has been imposed, whilst in (b) the shape of faces have been recorded accurately.

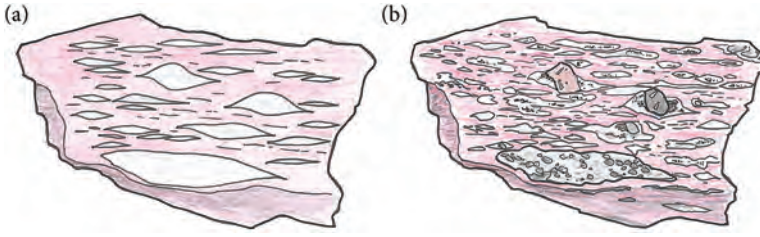

Figure 11.9 Showing two drawings of the same specimen of an ignimbrite with a eutaxitic texture. In drawing (a) the components have been drawn as simplified outlines and provides too little detail, in (b) the distribution of crystals and vesicles within fiamme are included giving much more value.

11.6 More examples

Examples of hand-specimen sketches from the field notebooks of the author are shown in Figure 11.10. Many of these sketches were drawn from hand-specimens after visiting localities by leaving an appropriate space in the notebook. Most could have been recorded adequately using photographs; however, there is value to having a complete record of observations within one place in a notebook.

Crystals of amethyst from a hydrothermally altered lava at Osilo in Sardinia are shown in Figure 11.10a. These sketches were drawn to illustrate the occurrence of amethyst prisms within drusy-lined vugs present in hydrothermal veins. Some doubly terminated crystals were observed with c-axes parallel to the drusy layer. Figure 11.10f also shows crystals

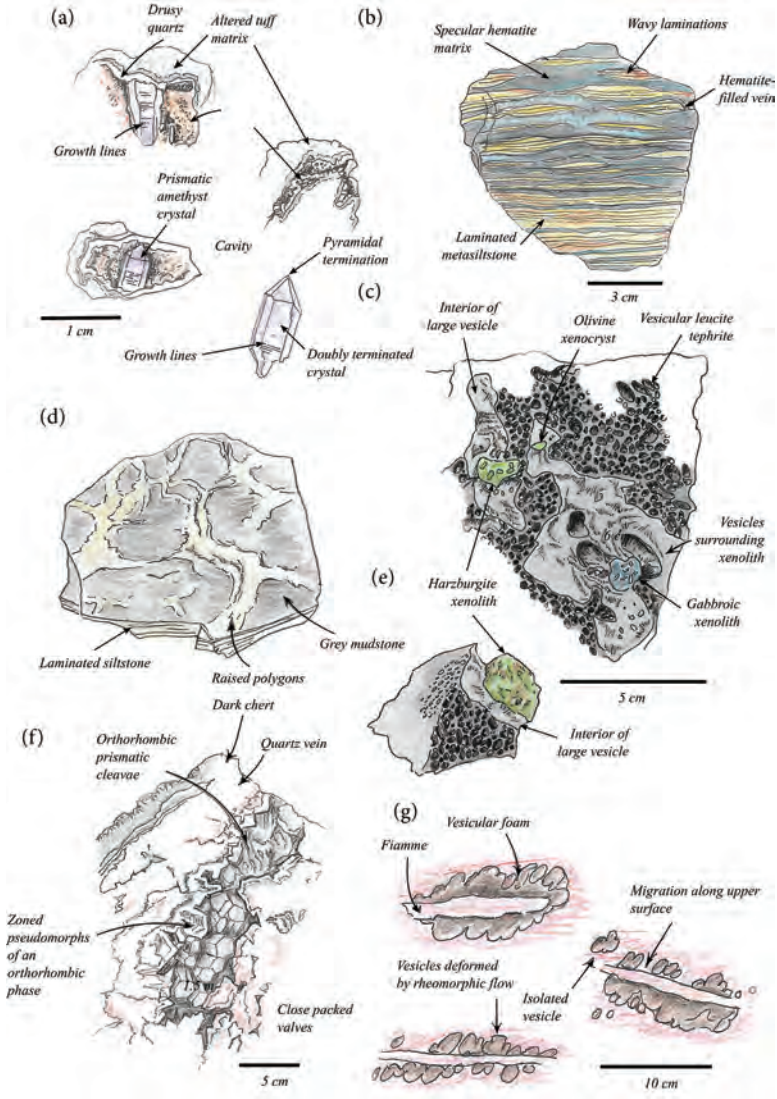

Figure 11.10 More examples of hand-specimen sketches from the author's field notebooks.

within a vein, this time from the Strelley Chert in the Pilbara of Australia. Here the sketch was undertaken to record the location of the crystals lining a vug in the centre of the vein. The crystals are pseudomorphs of an orthorhombic mineral that has been replaced by quartz, suggesting a complex paragenesis. These might have been anhydrite crystals.

Sedimentary hand-specimens are shown in Figure 11.10b and d. A specimen of banded ironstone from the Pilbara is shown in Figure 11.10b and was drawn to illustrate the relationship between the sedimentary laminations within the metasiltstone bands and the hematite-rich areas. Hematite veins suggest the iron-oxide distribution is at least in part caused by diagenetic redistribution after deposition. Figure 11.10d shows a specimen of Triassic siltstone with a mudstone drape on the upper surface from the Spanish Pyrenees. This specimen was drawn to record the irregular raised-rim polygons. These structures occur in sabkhas and playa lakes where evaporite crystallization within sediment causes lateral expansion.

Igneous hand-specimens are shown in Figure 11.10c, e, and f. A scoriaceous leucite tephrite from Sardinia is shown in Figure 11.10c and e and includes mantle and crustal xenoliths. The specimen was drawn to illustrate the occurrence of larger vesicles adjacent to the xenoliths. Particular attention, therefore, was given to the distribution of vesicles in the specimen and to colouring and shading. Figure 11.10g provides an example of peripheral diagram of features that were in situ. These are fiamme within an ignimbrite from Sardinia that are surrounded by vesicles forming cavities. Shading is used to emphasize the foam-like nature of the vesicular cavities.

11.7 Key concepts

Important concepts that apply when drawing hand-specimens are as follows:

- The outline of the specimen is important since it guides the placement of other features.
- Observation prior to drawing is required to identify the most important features.
- The petrology must be simplified to make drawing practical.
- Sufficient small-scale features must be drawn to illustrate texture.

12

Drawing rocks in thin-section

Generations of geologists have drawn thin-sections, viewed using a polarizing microscope, to illustrate the petrology and mineralogy of rocks. Today, however, optical microscopy is rarely used within scientific papers, with backscattered electron images, acquired by scanning electron microscopy, used instead. Optical mineralogy, however, provides information that such techniques cannot, including the identity of polymorphs, optical orientation, and twinning, and thus remains useful in the study of rocks. Given that electron microscopes are expensive to use, optical mineralogy remains the preferred method for preliminary examination of specimens and every geologist needs to be familiar with thin-section techniques.

Until recently, taking photographs of thin-sections required expensive cameras and specialized optics. However, adaptive optics on smartphones have enabled their cameras to take remarkably good pictures through microscope eye-pieces. Recording the textures and mineralogy of rocks through thin-section sketches, however, is a poor use of research time, but remains an important learning tool for undergraduate students. Drawing thin-sections encourages careful observation of features and aids thorough description and thus still has considerable value.

12.1 Polarizing optical microscopy of thin-sections

Thin-sections are slices of rock that are typically 30 μm thick, allowing light to pass through all but the most opaque minerals. Observations with a microscope are made under polarized light, in which the electromagnetic field vibrates in only one direction. Two modes of observation are used to observe textures: plane-polarized light (PPL) and cross-polarized light (XPL). In PPL the light is passed through a single polarizer, located between the light source and the sample. In XPL the light also passes through a second polarizer, located between the sample

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and the eye lens. The second polarizer is oriented with a polarization direction at 90° to the first and only light whose vibration direction has been changed during its passage through the sample can reach the eye. The change in polarization direction caused by a mineral is the result of light splitting into two rays, which vibrate at 90° to each other along specific vibration directions within minerals. The recombination and interference of the two rays once they leave the sample results in interference colours that can help in mineral identification.

Minerals can be identified by their properties in PPL and XPL and their change in appearance during rotation of the stage. In PPL the main observable properties are colour, cleavage, pleochroism, and relief (Figure 12.1). Colour in PPL often differs from the colour of hand-specimens and is usually not characteristic of particular minerals. However, several minerals do have typical colours that aid their identification, such as the honey-yellow of staurolite (Figure 12.1b) and the blue to purple colours of the amphibole glaucophane (Figure 12.1a). Pleochroism is the change in colour of a mineral as it is rotated on the stage and is also useful in identifying many minerals. Glaucophane, for example, has a characteristic blue to purple pleochroism and staurolite exhibits a change in the intensity of its honey-yellow colour.

Relief is a particularly useful property best observed in PPL that relates to the difference in refractive index between a crystal and its surroundings. High relief minerals surrounded by low relief materials appear embossed as if they are protruding from the surface. The high relief of several minerals makes them easy to recognize when combined with other properties, for example, garnet is high relief and is isotropic in XPL (see following paragraphs) and olivine tends to have higher relief than other associated minerals, is colourless in PPL, and lacks cleavage (Figure 12.1e).

Cleavage is useful in thin-section, but is seen in two dimensions as a cleavage trace. Often in thin-section, cleavage can be difficult to identify unless it is an excellent or good cleavage plane. It is, however, particularly useful to distinguish between amphiboles and pyroxenes in basal sections where the intersections of their two prismatic cleavages can be seen. Amphibole cleavages intersect at 124° whilst in pyroxene the angle is 90°.

Crystal shape in thin-section is related to crystal symmetry and habit. Euhedral crystals with perfect crystal shapes can be used to identify the symmetry of the mineral (Figure 12.1f). In two dimensions, however, this usually involves comparing the shapes of many crystals

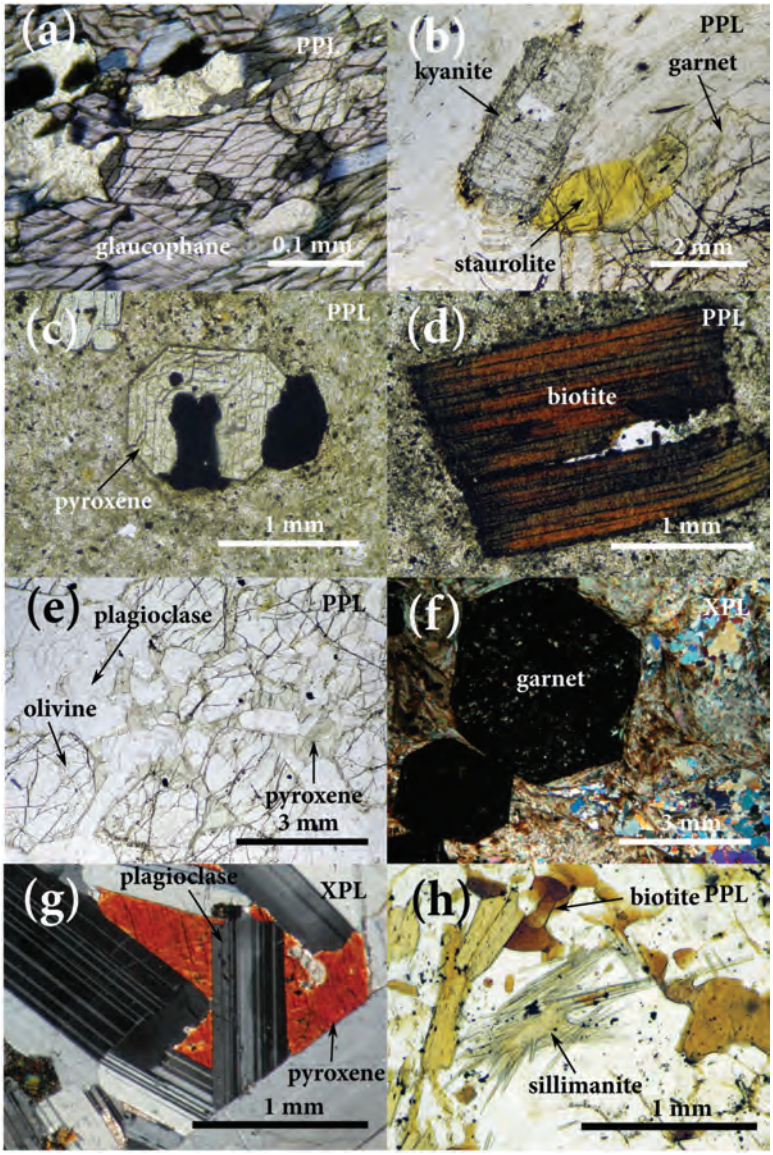

Figure 12.1 Illustrating the optical properties of some common rock-forming minerals.

to reconstruct the symmetry (as discussed in Section 12.2.4). Some characteristic sections through minerals, however, can reveal their symmetry, such as a hexagonal basal section—especially when combined with observations of extinction angle in XPL. Habit relates to crystal forms dictated by growth conditions. Some minerals commonly occur in a particular habit. For example, sillimanite often appears as fibrous radiating sheaths (Figure 12.1h), whilst kyanite is typically bladed.

In XPL the most important properties of minerals are extinction angle, interference colour, and twinning. Extinction is useful in determining the crystal system of a mineral and describes the change in brightness as a mineral is rotated in XPL. During rotation the amount of light passing through the eye-piece polarizer changes and once no light passes (i.e. the crystal is black) then the vibration directions of light in the crystal match the vibration directions of the polarizers. These directions relate to the crystal structure. Cubic minerals are extinct when viewed from any direction (i.e. they are isotropic) and thus are always black in XPL (Figure 12.1f). Glass is also characteristically isotropic. Note that opaque minerals do not allow light to pass in either PPL or XPL and differ from isotropic minerals. Crystals that become extinct when their elongation directions (or length-parallel cleavages) are parallel to the polarizers (N-S and E-W) are said to have straight extinction and thus have orthorhombic, tetragonal, or hexagonal crystal symmetries. Finally, those minerals with extinction directions inclined to the elongation direction of crystals have monoclinic or triclinic crystal symmetries.

Two unusual forms of extinction are also useful to note. When the extinction direction changes across a mineral it is described as undulose. This type of extinction arises owing to deformation of the crystal lattice and is most common in quartz, but can occur in many other minerals, particularly in metamorphic rocks. Bird's eye extinction is a pattern that appears speckled at high magnification and is very common within mica-group minerals such as muscovite, biotite, phlogopite, and the related mineral chlorite (Figure 12.1d).

Interference colours form a repeated spectrum of colours and are an important property that allows minerals to be identified (Figure 12.2). All minerals, however, exhibit a range of interference colours that vary from black to a maximum. The colour observed in any particular crystal within a thin-section depends on the viewing direction. Interference colour thus also provides a means of determining the orientation of the crystal, particularly when combined with other features, such as cleavage

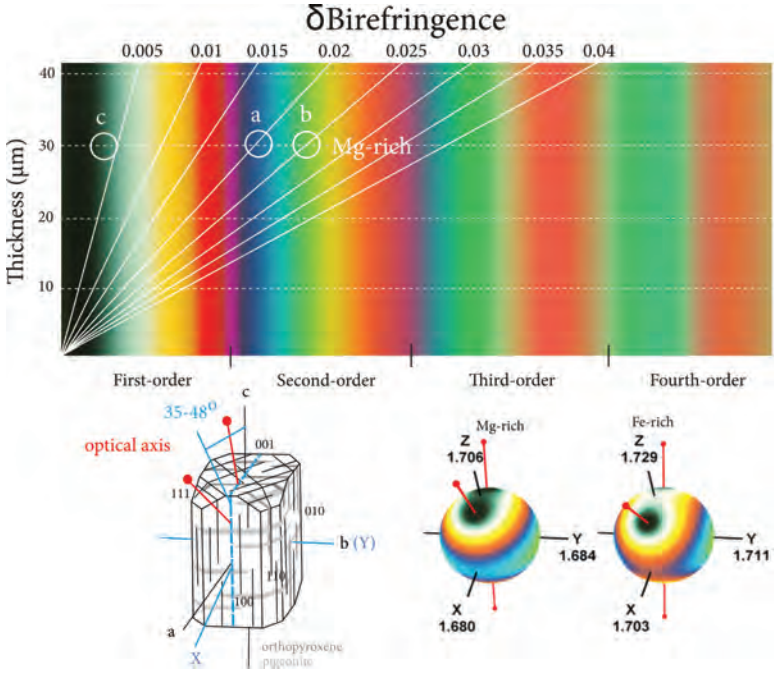

Figure 12.2 Showing the interference colours exhibited by minerals in cross-polarized light. Interference colours change depending on thickness of the section along lines of equal birefringence. Colours also change with orientation of a crystal in the section. An example of how the interference colours of augite change with orientation is shown.

and crystal shape (see Section 12.2.4). Identifying the maximum interference colour, therefore, means looking at many crystals of the same mineral in a thin-section (identified as the same mineral by other properties such as relief and colour).

Twinning is an important property of minerals in XPL that can be valuable in mineral identification. Twinning can be seen in thin-section in the different extinction angles of a crystal either side of a twin plane. The number and arrangement of twin planes define different types of twinning, for example, penetrative twins, like Carlsbad twins, and repeated lamellar twinning, such as polysynthetic twinning. The polysynthetic twinning of plagioclase (Figure 12.1g) and tartan-twinning of microcline are particularly characteristic of these minerals and allow easy identification.

Other features of minerals that can be observed in thin-section are also useful in identifying minerals. Alteration products, for example, are sometimes characteristic. Feldspar tends to alter to sericite, a fine-grained mixture of clay minerals and muscovite, which often gives these crystals a cloudy appearance in PPL. This makes them easy to distinguish from quartz, which tends to lack alteration. Olivine is also typically sensitive to weathering and often alters to a red-brown material known as iddingsite.

Ultimately, identifying minerals confidently in thin-section involves combining all the observable properties to obtain a likely identity. A particularly useful criteria is occurrence, since knowing which minerals are commonly found together, in what rock types, means a shortened list of likely minerals. Although subject to error, and seemingly cheating, this tactic will enable correct identification in 99 per cent of cases, even though it requires some iterative thinking, since mineral identification is also required to identify rock type. The most common minerals found within a wide range of rock types is described in Section 11.1 on hand-specimens. For more information on mineral identification in thin-section refer to an optical mineralogy textbook, such as *Optical Mineralogy* by William Ness.

12.2 Drawing styles and tactics

The three main tactics in drawing thin-sections are illustrated with examples below. Each has its advantages and disadvantages.

12.2.1 Single field of view

Traditionally thin-section images were drawn within a circular outline representing a single field of view. Usually the view of the thin-section was drawn in PPL and in XPL, often with half the view drawn in each mode. An example of this type of diagram is given in Figure 12.3 and shows a garnet-mica-schist from the Sezio-Lanzo zone of the Alps in northern Italy.

Drawings of a single view begin with finding a location in the sample that best reflects the petrological and mineralogical properties of the specimen. Unless the sample is fine-grained, it is highly likely that any single view will not be representative, and thus a subjective choice must be made about which features will be illustrated. The non-representative nature of single view thin-section images for coarse-grained rocks is their most significant disadvantage.

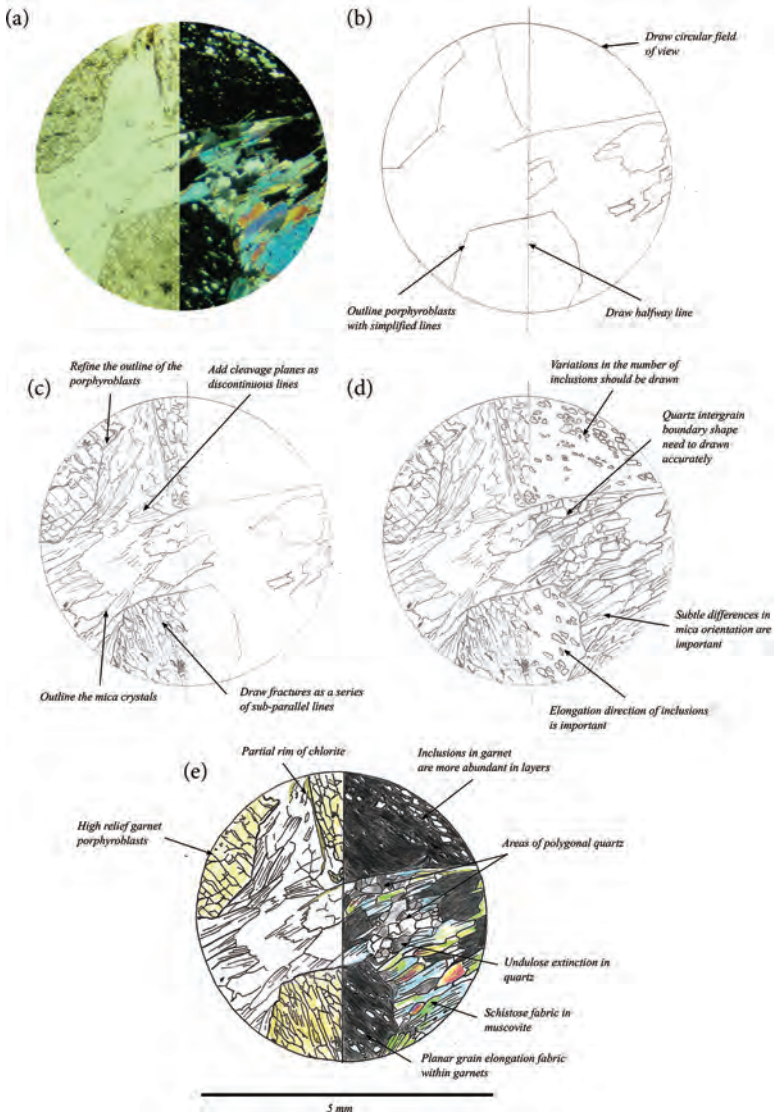
(a)
(b)
Draw circular field of view
Outline porphyroblasts with simplified lines
Draw halfway line
(c)
Refine the outline of the porphyroblasts
Add cleavage planes as discontinuous lines
Outline the mica crystals
Draw fractures as a series of sub-parallel lines
(d)
Variations in the number of inclusions should be drawn
Quartz intergrain boundary shape need to drawn accurately
Subtle differences in mica orientation are important
Elongation direction of inclusions is important
(e)
Partial rim of chlorite
Inclusions in garnet are more abundant in layers
High relief garnet porphyroblasts
Areas of polygonal quartz
Undulose extinction in quartz
Schistose fabric in muscovite
Planar grain elongation fabric within garnets
5 mm

Figure 12.3 A sketch of a single field of view of a garnet-mica-schist from northern Italy.

Once a view has been chosen a circle is drawn to represent the field of view either with a set of compasses or by drawing around a cylindrical object. The field is then split into two with a vertical line, as shown in Figure 12.3b. The first step in drawing the specimen is to sketch the outlines of the largest or most euhedral crystals; in this case three porphyroblasts of garnet are drawn first. Initially their outlines are drawn as simplified straight lines. Areas where the sample has been plucked and only resin remains can also be drawn. Switching between PPL and XPL during drawing allows features from both to be incorporated in the sketch.

Smaller crystals can now be added to the drawing. In this case the matrix is dominated by crystals of muscovite and quartz whose boundaries are difficult to distinguish in PPL, owing to their similar relief. Some interpolation of the faint boundaries seen in PPL must be used by switching to XPL, as shown in Figure 12.3c.

Details can now be added to the sketch. Within the garnets a subparallel parting of fractures is prominent in PPL, and inclusion trails of quartz are seen in XPL. The shape and elongation direction of inclusions in this specimen are particularly important to record. Linear trails of quartz inclusions with the same grain elongation fabric usually indicate formation of the garnet during the first phase of deformation when a planar foliation is formed. The different orientations of grain elongation in different garnet crystals, compared with the surrounding muscovite, suggest the garnets grew before the formation of the later fabric. Areas of mosaic quartz are also present at some locations between the garnet porphyroblasts. Quartz often has recrystallized within metamorphic rocks and exhibits polygonal textures. Migration of quartz through pressure-solution may also have occurred into pressure shadows located near the rigid garnet porphyroblasts. Cleavages can also be added to the mica minerals as discontinuous lines drawn where the cleavage is most apparent. It is important not to draw cleavage schematically.

The final stage of this drawing is to add descriptive labels and scale. Labels should be quantitative and can include information on the abundance of phases. The field of view of the microscope at the drawn magnification should also be added since this has more information that just '×10 magnification'. Colour is essential in thin-section diagrams of coarse-grained rocks and involves trying to reproduce interference colours as accurately as possible with the palette available.

12.2.2 Expanded view

A second tactic in drawing thin-section diagrams is to construct an image of a wider area of the specimen than a single view at the lowest magnification. These diagrams are difficult to draw since moving the field of view can cause momentary loss of position. Keeping the stage rotation fixed, however, helps prevent losing the position completely. Expanded view diagrams are particularly useful in illustrating the overall texture of rocks in thin-section, but have the disadvantage that properties used to identify minerals are less easily included at lower magnifications.

An example of an expanded view drawing is given in Figure 12.4 and shows a Jurassic limestone containing bioclasts, mainly of bivalve shells. The matrix of the limestone consists of fine-grained lime mud (micrite). In the Dunham classification system, described in Section 11.2, this specimen is termed a bioclastic packstone. The field of view of the photograph is 1 cm.

The first task in drawing the specimen is to locate an area that shows a representative texture. The main features, which in this case are the outlines of the bivalve shells, can then be drawn. These are most easily seen in PPL rather than in XPL. A useful method in drawing features larger than the field of view is to draw one object at a time by moving the view to trace its outline. The drawing then expands outwards, shell by shell, until sufficient area has been covered to illustrate the texture, as shown in Figure 12.4b.

Detail can then be added to the sketch. In this case both PPL and XPL features will be drawn on either side of the diagram, since both have significant interpretations. In PPL layering is observed within the valves with up to four layers of different thickness preserved. The boundaries between the layers are indistinct and are drawn as discontinuous short lines, broadly parallel to the exterior of the shell. Opaque organic matter is present as discontinuous layers along around 25 per cent of the shells and is highly variable in thickness. It is present around broken as well as whole shells and thus is probably not a remnant of the membranes of the bivalve, such as the periostracum that coats the outer surface. It may, therefore, relate to micro-organisms that were feeding on the organic material present within shells. The opaque matter can be drawn using solid pencil lines by scribbling the pencil to approximate the shape of the layers.

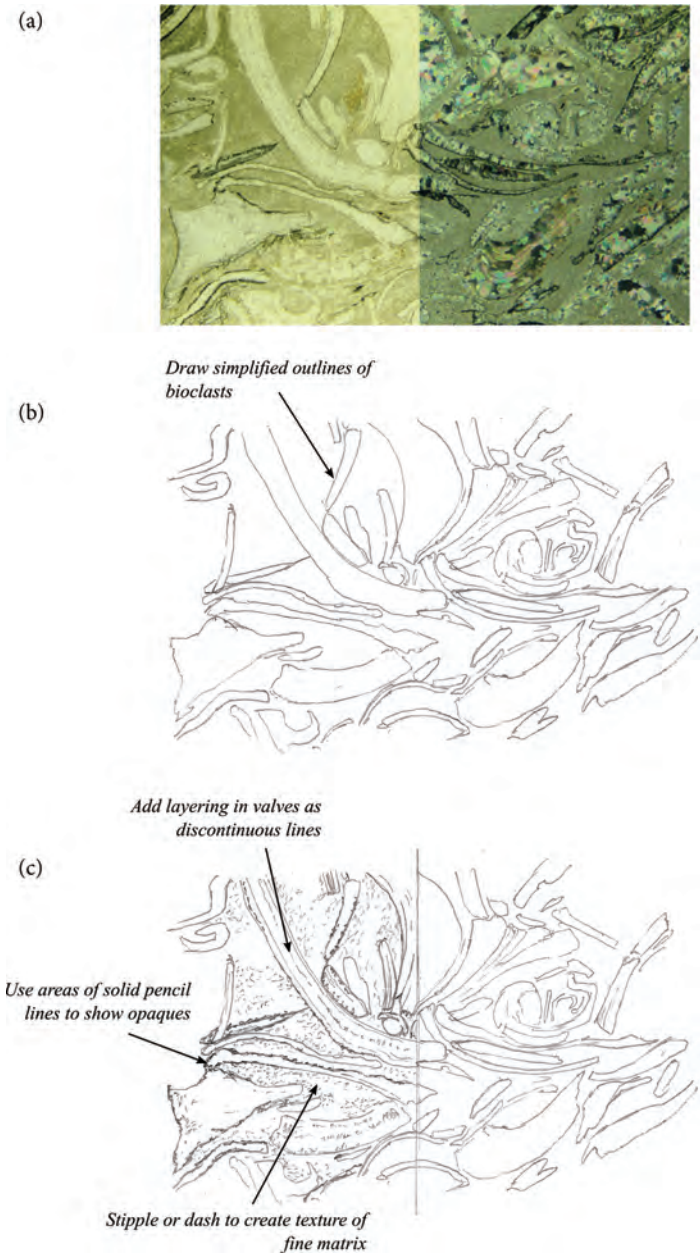
(a)
(b)
Draw simplified outlines of bioclasts
(c)
Add layering in valves as discontinuous lines
Use areas of solid pencil lines to show opaques
Stipple or dash to create texture of fine matrix

Figure 12.4 Initial stages of a sketch of a bioclastic packstone from Dorset in the UK.

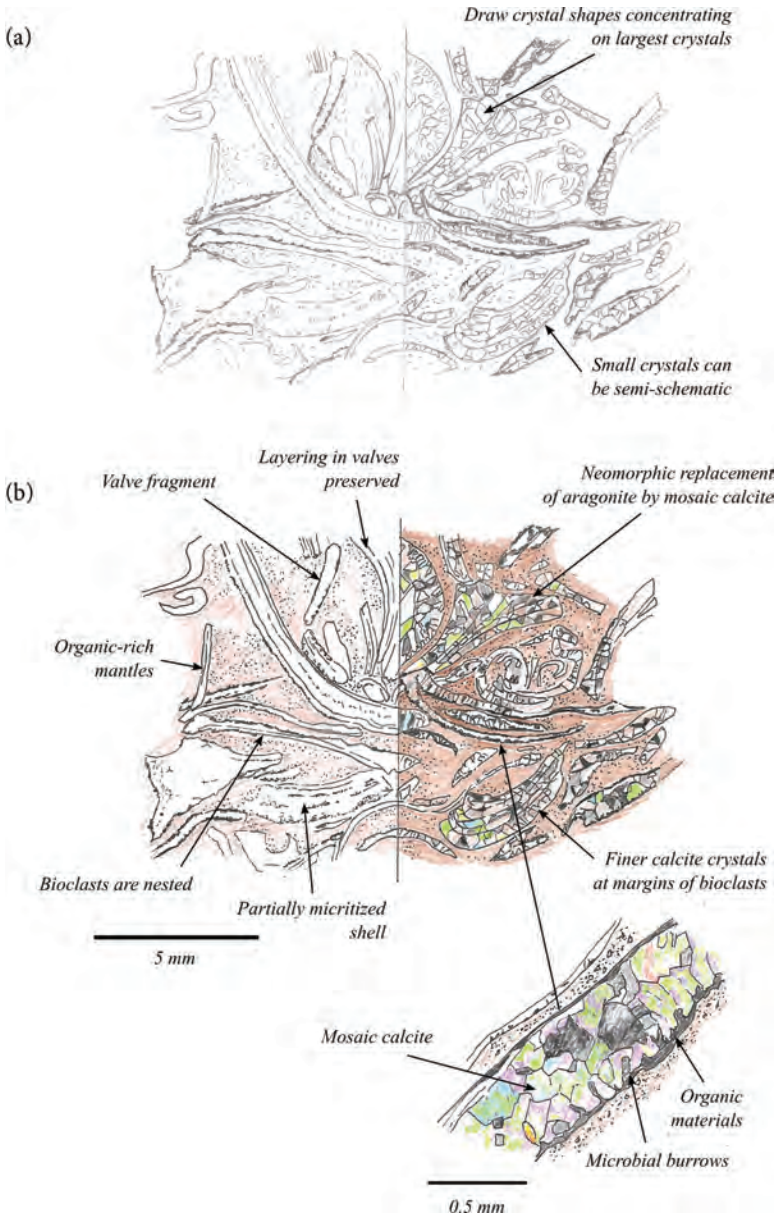

Figure 12.5 The final stages of a sketch of a bioclastic packstone.

In XPL many calcite crystals can be seen within the bioclasts and vary considerably in size with the smallest crystals, often with a tabular form, towards the margins of the shell. Many of the crystals extend across the layering within the shells suggesting they form by neomorphic replacement of original aragonite. Drawing all the crystals is not possible, however, the largest can be drawn as accurately as possible, and areas of finer-crystals can be indicated by drawing semi-schematic grain boundaries, as shown in Figure 12.5a.

Some representation of the matrix is also required; however, the grain size is too small for grains to be drawn accurately. Stippling can be added to indicate the presence of a lime-mud matrix and applied where individual grains are most apparent. The distribution of stipples should be random to show this is not a schematic pattern. This approach to very fine-grained areas is also useful in drawing thin-sections of volcanic rocks.

Finally, labels, scale, and colour should be added. In the case of this sketch, where the structure of the shells provides insight into their diagenetic alteration, a higher magnification peripheral diagram has also been added showing a cross-section of an individual valve (Figure 12.5b). Interesting features illustrated in the diagram are microscopic pores filled with opaque organic matter that penetrate the shell. These may represent burrows made by micro-organisms prior to diagenesis.

12.2.3 Composite thin-section sketch

The final tactic in drawing thin-sections is a composite diagram that attempts to illustrate texture by combining features from different locations within a specimen. This type of drawing is semi-schematic and of most use where significant features are dispersed over a much larger area than a single field of view at lowest magnification.

An example of a composite thin-section sketch is given in Figure 12.6 and shows a pitchstone—a glassy rhyolite that has undergone devitrification. This specimen is from the Isle of Arran in Scotland.

Drawing a composite diagram first requires a thorough observation of the entire thin-section to evaluate which features should be included. Typically, then a single field of view is chosen as the basis for the sketch and a proportion of its most important features are included. In this case two plagioclase crystals surrounded by rims of fibrous feldspar are chosen. A number of spherulites with concentric structures are also present in this field of view (Figure 12.6b). Spherulites and the rims on

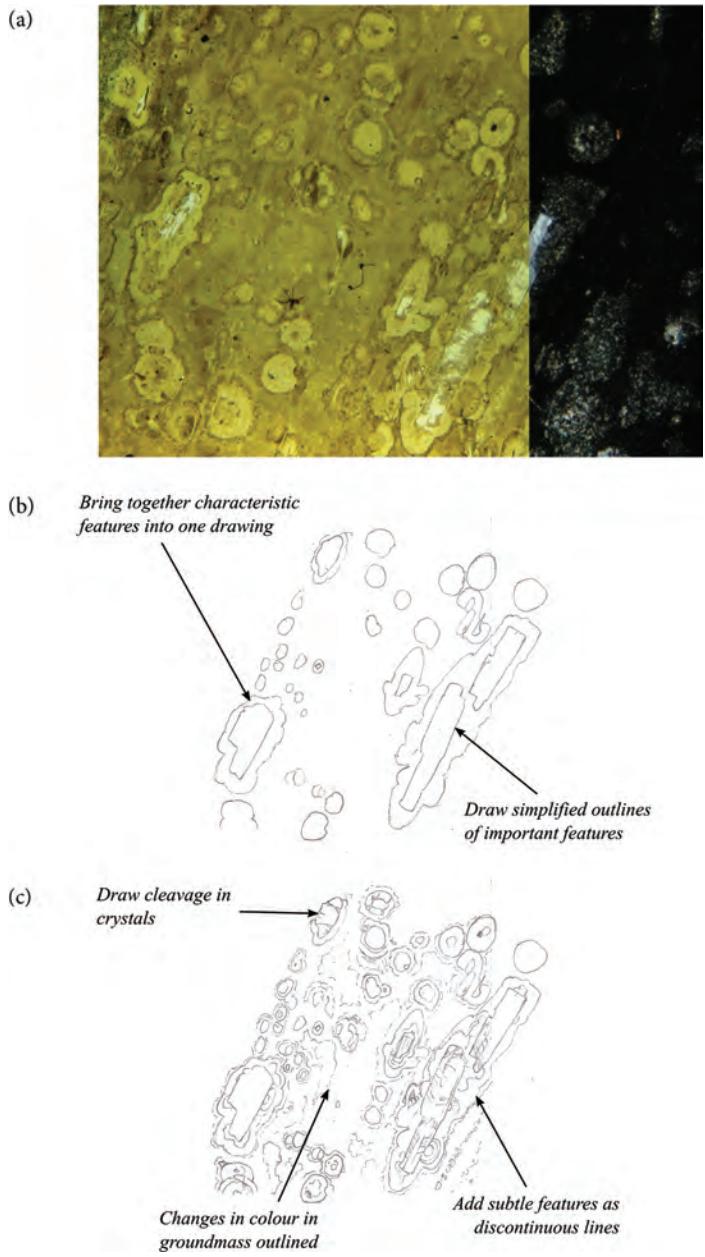
(a)
(b)
Bring together characteristic features into one drawing
Draw simplified outlines of important features
(c)
Draw cleavage in crystals
Changes in colour in groundmass outlined
Add subtle features as discontinuous lines

Figure 12.6 The initial stages of a sketch of a pitchstone from the isle of Arran.

the plagioclases form as a result of heterogeneous nucleation, where fibrous feldspar crystallites utilize small areas of crystal structure as a foundation on which to begin growing. Spherulites are typical of the crystallization of high viscosity rhyolitic magmas particularly at low temperatures during devitrification of glass.

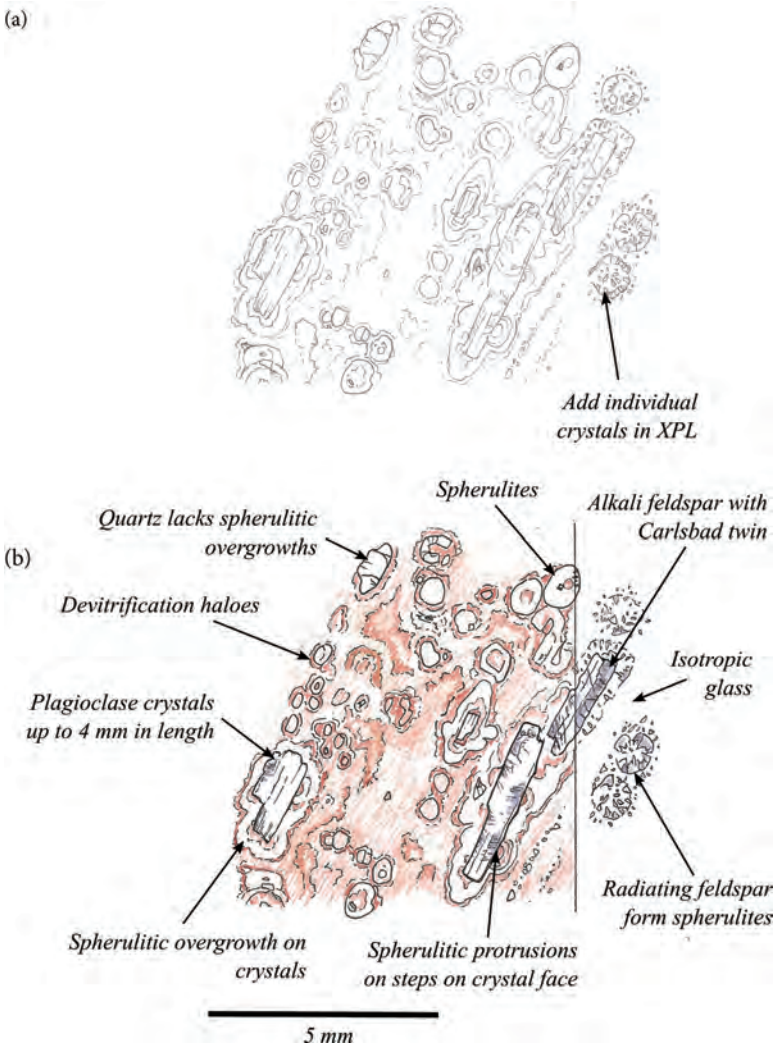

Figure 12.7 The final stages of a sketch of pitchstone.

One relevant feature is not present within this field of view. Rounded quartz crystals are present in the thin-section and are not surrounded by spherulitic rims—suggesting that the structure of quartz does not provide an adequate nucleus for the growth of the feldspar crystals. The quartz crystals are rare in the thin-section and although a field of view containing quartz could be drawn, there are none that also have good examples of spherulitic rims on plagioclase. A quartz crystal can, however, be included in this drawing from another location since its position within this rock has no particular significance. This composite approach to constructing a thin-section diagram is appropriate for any sample that doesn't have a long-range structure. Care should be taken, however, not to add features that are out of context.

The final stages of this sketch are to label and add scale. Colour can also be added since there are subtle differences that are likely to relate to the diffusion of components during the devitrification of glass. In this sample XPL provides relatively little information except for insights into crystal orientation within spherulites. A small area showing the specimen in XPL has been included in Figure 12.7b. Much of the sample still consists of glass and is thus isotropic. Rather than colouring the entire area black the glass is simply labelled.

12.2.4 Crystal orientation diagram

Another type of diagram sometimes drawn for thin-sections focuses not on the petrology or texture of the rock but on the optical properties of individual minerals. These crystal orientation diagrams combine views of several crystals in order to exhibit the change in interference colours, crystal shape, extinction directions and cleavage orientations with plane of section. Crystal orientation diagrams are usually only possible when crystals have euhedral shapes.

An example of a crystal orientation diagram is given in Figure 12.8 and shows hornblende phenocrysts from a thin-section of andesite from Fiji. Individual crystals were selected from the thin-section that represent different planes of section through hornblende crystals. Each crystal was drawn without the surrounding groundmass with a focus on accurate outlines and realistic representation of cleavage. Inclusions and twinning were also included where present. The extinction directions, that represent the projections of the X, Y, and Z optical axes, were also drawn. The relationship between the crystallographic and optic axes can be obtained from reference diagrams, as shown in Figure 12.8.

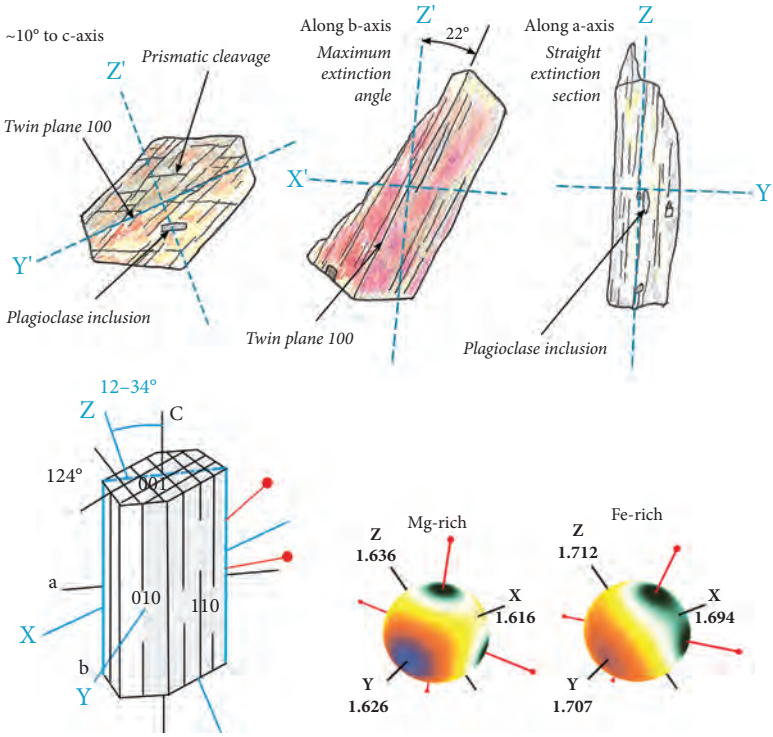

Figure 12.8 Crystal orientation diagrams of crystals of hornblende from an andesite from Fiji.

This diagram also shows the variation in interference colour in terms of viewing direction as two birefringence spheres for iron and magnesium-rich end-members of hornblende.

The crystals shown in Figure 12.8 demonstrate some important features of monoclinic crystals, such as hornblende. The maximum extinction angle is seen when viewing along the b-axis (plane 010) and also gives the maximum interference colour. In this case this is a first order red suggesting this hornblende has an intermediate composition between the two end-members.

12.3 Taking photographs of thin-sections

The adaptive focus on smartphones is sufficient to photograph thin-sections. The procedure involves holding the camera over the eye lens of

the microscope. It will take some trial and error to find the correct height above the lens to hold the camera in order to focus properly on the specimen. Small movements of the camera to the side or vertically will often cause the focus and brightness of the image to change, meaning many photographs must be taken to obtain a decent image. The process is just as easy, and much more convenient, than using a specific camera set-up.

12.4 Common mistakes

12.4.1 Schematic representation

The sketching of thin-sections always involves the identification of the minerals and examination of textures prior to drawing. There is a tendency, therefore, to draw crystal shapes and cleavages that conform more closely to ideal mineral properties than was observed, as shown in Figure 12.9. There is some value in such diagrams; however, they are too

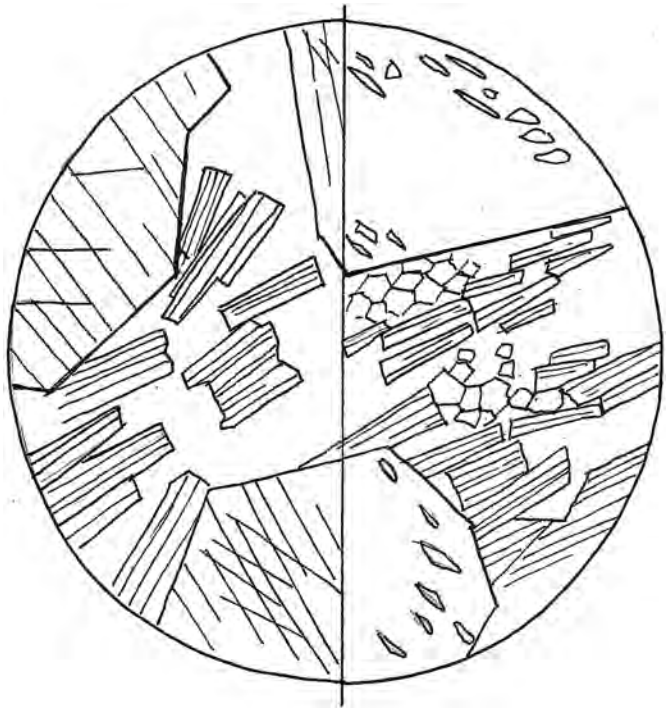

Figure 12.9 An overly schematic thin-section drawing.

schematic to illustrate the detailed elements of the petrology that often reveal important rock-forming processes.

12.5 Key concepts

In this chapter, several key concepts and methods were introduced:

- Carefully consider whether drawing thin-sections is worthwhile.
- Use a tactic to draw the specimen that is appropriate for the rock type and its components.
- Draw crystal or component shapes first. It is useful to work outwards from a single object.
- Add detail from PPL and XPL.
- Crystal orientation diagrams are useful in recording the optical properties of individual minerals.

13

The art of maps

Creating geological maps is a fundamental part of Earth Science and a crucial activity in any Earth Science degree. It is difficult to imagine geology without the concept of a map, and yet the early history of the subject lacked the concept of stratigraphy, units, and formations that define mappable units. It wasn't until the maps of William Smith in 1815 that national geological maps appeared as powerful tools in understanding structures and sequences.

Geological maps can be subdivided into precision maps, where field observations are recorded on a base topography map in order to identify the outcrop pattern of mappable units, and sketch maps, in which the spatial relationships of units or their component lithologies are recorded at a higher scale within a notebook. This chapter will focus on sketch maps. However, an overview of good practice in precision geological mapping will be included since many symbols and techniques are similar.

13.1 Geological mapping

The fundamental concepts of geological mapping are simple. Exposures of rocks are plotted on a base map in the field, together with measurements of bedding, cleavages, folds, and faults. Boundaries between mappable units are then identified using the exposures and extrapolated across the map at variable levels of confidence.

13.1.1 What to map

What constitutes a mappable unit depends on the scale of the map and on the distinction between the stratigraphic units present. By definition formations consist of a set of lithologies that are sufficiently distinct that they can be distinguished from other formations and have sufficient lateral extent to be useful in mapping. A formation consisting of mudstones interbedded with limestones is, for example, distinct from a formation consisting of interbedded mudstone and sandstone. If the

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boundary between the two is gradational, a threshold can be defined as the boundary between the two (e.g. 50 per cent sandstone beds). Smaller units, however, can also be mapped if they are sufficiently distinct, for example, a 20 m thick limestone within a formation consisting mainly of mudstone can be mapped even if it disappears laterally. These units are considered members and are useful marker horizons. Usually the first task in mapping is to define the mappable units with type descriptions. These may, however, evolve over the fieldwork.

Scale is also an important consideration in what can be added to a geological map. At a base map scale of 1 in 10,000, a unit ten metres wide is 1 mm in width on the map, often too small to include. Small geological features, however, such as metre-sized dykes and sills can be included on a map as coloured lines but mostly cannot be followed very far along strike.

13.1.2 How to plot exposures

The most crucial part in plotting exposures is knowing their positions on the map. Some positions are easy to find, such as the intersection of roads and rivers, the corners of walls, or power lines. The shape of contours is also useful in finding positions and involves the ability to visualize topography from the contour lines. Compass bearings to known locations on a map can also provide position through triangulation but require a direct line of sight. Global positioning systems (GPS) are commonly used for position location; however, they are not infallible and suffer from variable accuracy. It also takes time to find a point on the map from coordinates. By far the best way to find a position is to walk with a map out and follow your location on the map. When arriving at the next locality, the position is, therefore, already known.

Plotting an exposure first involves adding the exposure pattern as a line showing the shape of the exposed rocks. Making the pattern as realistic as possible is beneficial since many outcrops are elongate parallel to bedding. When an outcrop is very small it is acceptable to exaggerate its size. When the exposure is very large, the rocks that can be easily seen can be outlined. At the Royal School of Mines green indelible ink is used to outline exposures. Each exposure should also be labelled with the same locality number as in the notebook. The majority of exposures should have a locality; however, it is permissible to sight-in inaccessible exposures without visiting them. These should still be mentioned in the notebook.

Measurements should be added directly to the map in the field using symbols. The bedding symbol, which consists of a bar with a central tick in the direction of dip, should be positioned where it was measured. Other measurements are added as symbols connected to the centre of the bedding symbol. Either just dip or dip and dip direction (or strike direction and dip) should be added adjacent to the symbol. Different colours can be used for different deformation events for structural measurements. An example of symbols and a field map is shown in Figure 13.1.

13.1.3 Adding boundaries

Boundaries should be added systematically to the map. Where possible, boundaries should be drawn in the field, in pencil at first. It is important to classify boundaries in terms of confidence. An observed boundary between units can be shown as a solid line, with a different colour used for faults. Constrained boundaries, for example, by close exposures or breaks in slope, should be drawn as lines consisting of long dashes, whilst inferred boundaries, often through areas of no exposure, can be drawn with short dashes. Fault traces are also decorated with symbols to show their sense of movement, as shown in Figure 13.1.

The dip and strike of bedding should be considered when adding a boundary. On flat ground a boundary will be oriented parallel to the strike of bedding, whilst on a slope the boundary will run down slope of the strike line in the direction of dip, and up slope of the strike line in the opposite direction to dip. Only a horizontal boundary will run parallel to contours. A vertical boundary, in contrast, trends straight across the landscape. If boundaries are not consistent with bedding then they may be overlying an unconformity or they may be faulted.

Bedding contours, which are lines marking equal height on a boundary, can be used to trace boundaries through their intersection with the corresponding contour. Where the dip of bedding changes, however, bedding contours can be difficult to use. The use of bedding contours is demonstrated in Figure 13.2.

13.1.4 Annotations on maps

Annotations should always be added to field maps to provide relevant additional information. Labels such as ‘no exposure’, ‘sandstone in soil’, and ‘break in slope’ help guide interpretations. Particularly unique

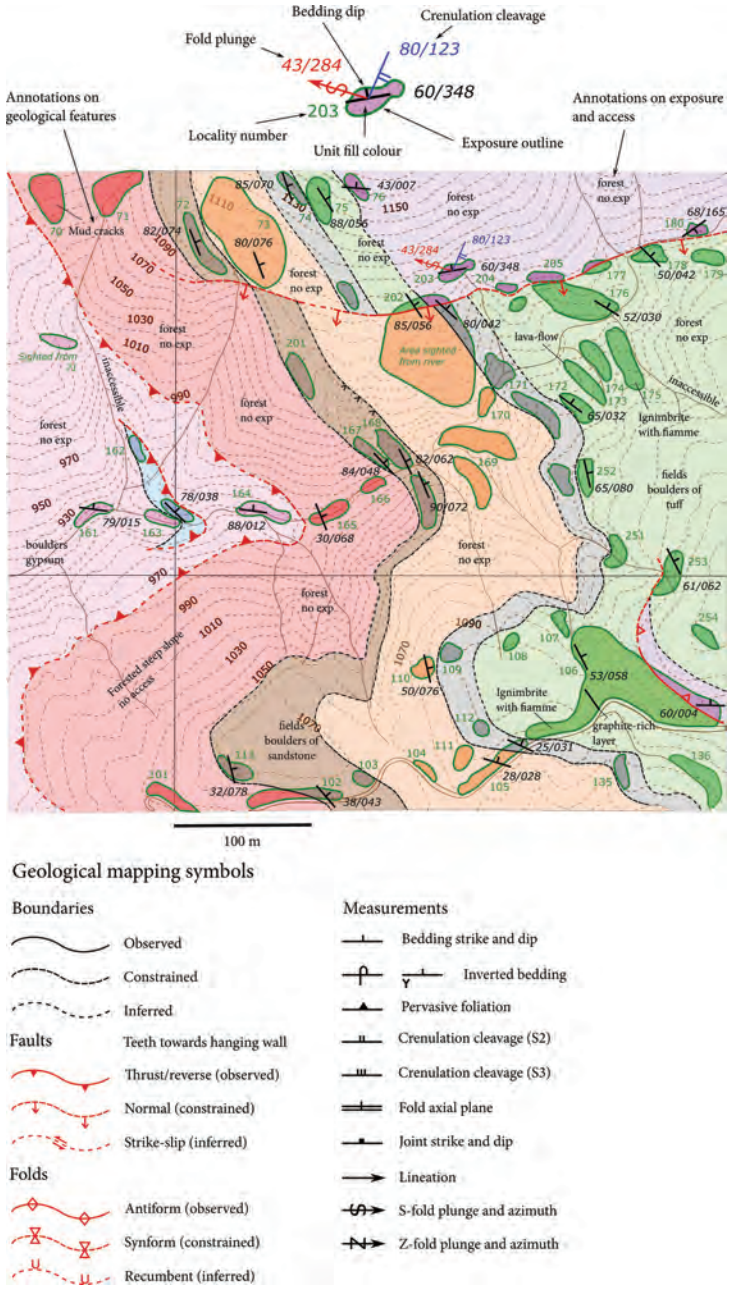

Figure 13.1 An example field map together with symbols and exposure style.

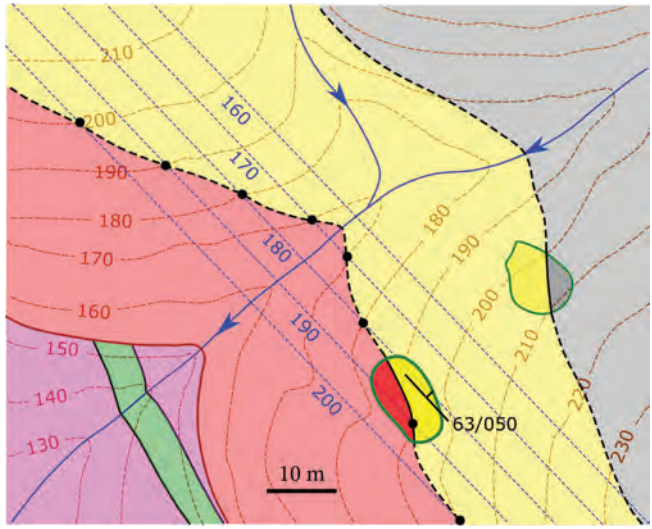

Figure 13.2 An example of how to extrapolate a boundary using bedding contours. Blue dashed lines show the heights on the boundary and are constructed from dip measurements.

localities can also be highlighted in the map with labels where there is room. Text annotations added after mapping, such as interpretations, are considerably less useful. Symbolic annotations, such as the axial traces of folds, should also be added to field maps.

13.1.5 Mapping tactics

Perhaps the most efficient tactic in mapping is to conduct several approximately parallel traverses across the area following routes that are likely to have exposure. River courses, ridge paths, and minor roads all tend to have good exposure. Boundaries can be extrapolated between parallel traverses using bedding measurements. Where mismatch occurs then investigation of the intervening area can be conducted to trace the course of a boundary across country; often this leads to the discovery of faults or fold axial traces. Whilst conducting traverses particular attention should be made to the surrounding landscape. Often boundaries, particularly between units of different competency, can be readily seen from a distance from changes in slope and marked in pencil on the map. Often the extension of boundaries encountered on one traverse will be seen whilst undertaking a parallel traverse across country.

13.2 Sketch maps

Often in the field a small area is found comprising one or more outcrops with complex spatial relationships which are too restricted in area to plot onto a field map. These areas can have particularly important interpretations for the geology of an area and are difficult to record without creating a higher resolution map. The best solution for such areas is to create a sketch map in a notebook that records the spatial information together with lithological and structural details. At this higher resolution, individual lithologies, rather than formations, can also be mapped to provide enhanced constraints on palaeoenvironment. There are several different reasons to create a sketch map, all of which require slightly different tactics.

13.2.1 Sketch maps of complex localities

Occasionally a single locality is encountered that has sufficient structural complexity that a sketch map provides the best means of recording it. Usually such localities consist of exposures with large horizontal surfaces that cannot be recorded as a field sketch without considerable perspective complicating the geometry of features.

A map of a single outcrop from Kinlochleven in Scotland is shown in Figure 13.3. It illustrates how a sketch map can be used to record

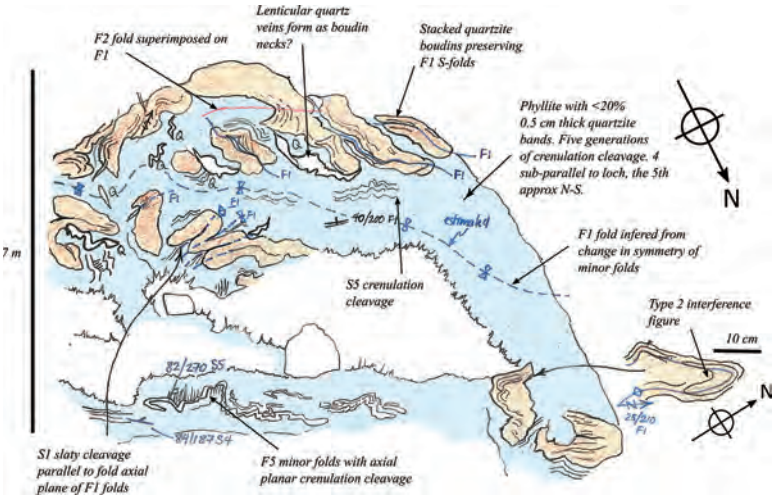
F2 fold superimposed on F1
Lenticular quartz veins form as boudin necks?
Stacked quartzite boudins preserving F1 S-folds
Phyllite with <20% 0.5 cm thick quartzite bands. Five generations of crenulation cleavage. 4 sub-parallel to loch, the 5th approx N-S.
F1 fold infered from change in symmetry of minor folds
S5 crenulation cleavage
Type 2 interference figure
10 cm
7 m
S1 slaty cleavage parallel to fold axial plane of F1 folds
F5 minor folds with axial planar crenulation cleavage
N

Figure 13.3 A sketch map showing the structure of an outcrop of Neoproterozoic phyllite and quartzite from Kinlochleven in Scotland.

complex spatial relationships more readily than a field sketch. This outcrop exposes superimposed fold structures within phyllite containing quartzite beds. A first generation (F1) isoclinal fold can be identified in the outcrop by the change in symmetry of minor folds in the quartzite bed on either limb (see Chapter 6 on superimposed folding in metamorphic rocks). Several generations of crenulation cleavage and minor folds of later deformation events are also present.

To create a sketch map of such an exposure, the outline should be added first. The relative size of the exposure is important to ensure accuracy and can be determined by counting paces or using a measuring tape. A scale bar should be added at this stage, to assist the addition of objects to the map at the correct scale, and a north arrow added to help constrain the orientation of features. Detail is then added by walking around the outcrop and drawing individual features and structures. A compass clinometer can be used to ensure that features are added in the correct orientation by drawing guidelines. Measurements made whilst inspecting the exposure can be added directly to the sketch map using the appropriate symbols. Labels on lithology and descriptions of structures should also be included during the process to indicate where observations were made.

Sketch maps of important individual localities provide high resolution spatial data that can prove crucial in interpretation of an area. Depending on light conditions, photographs taken at many different angles of such outcrops can be used to create a digital three-dimensional model by photogrammetry, as described in Section 16.1.

13.2.2. Sketch maps recording lateral variations

Where significant lateral variation in lithology occurs within a unit, in an area with a large degree of exposure, a sketch map can provide a means of recording the geology at higher resolution. Lateral variations are often important clues to minor changes in depositional environment that can give a greater insight into sedimentary processes and detailed paleogeography.

A sketch map of a locality in the Spanish Pyrenees is given in Figure 13.4 that shows Carboniferous black shales interbedded with siltstones overlying pyroclastic deposits. The sequence is inverted. Stratigraphically above the shales, red mudstones and siltstones containing slump folds are exposed. An interesting feature in the outcrop is the presence of several chert beds within the black shales. The cherts

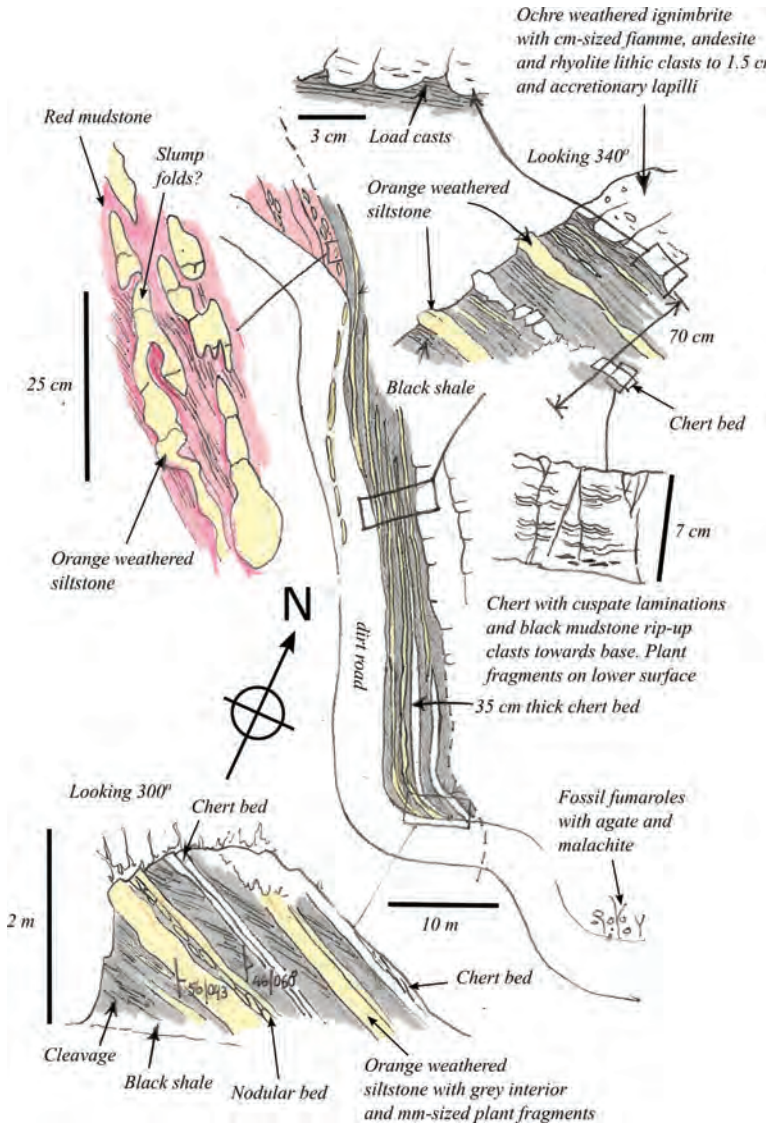

Figure 13.4 A sketch map recording the change in lithologies across a large area of exposure in the Spanish Pyrenees. The map also includes several field sketches.

are laterally discontinuous over a few tens of metres. To record the location of chert beds within the sequence and the change in their abundance laterally the sketch map was created.

The dirt road was added to this map first, with its orientation determined using a compass and distances measured by counting paces. A scale and north arrow were both added at the beginning of the sketch to allow bearing lines to be drawn with a compass to plot the road's position accurately. The extent of the outcrop of interest was then added. Variations in the lithology were drawn on the map by recording each bed and adding labels. Several interesting features were encountered during creation of the map and were recorded using small peripheral field sketches, each with their own scale, looking direction, and labels.

13.2.3 Sketch maps of numerous small exposures

Perhaps the most useful sketch maps are those that record areas consisting of multiple exposures that record complex spatial relationships at a resolution too high to be included on the available base maps. A sketch map can be used to record the geology at an enhanced resolution, with the objective of transferring a simplified version to a field map once the most important features have been identified.

An example of a sketch map of numerous small exposures is shown in Figure 13.5 and records closely spaced faults within the thrust imbricate at Assynt. The map shows the repetition of sequence that allows thrusts to be located since the thrust planes are not exposed. Thrust duplexes are described in more detail in Section 14.2.2.

The first stage in creating this map was to outline the area to be mapped. In this case the area was bound by the loch, two roads, and a fence. Since 1 in 10,000 maps were being used, a higher resolution version was drawn into the field notebook by scaling up the field map using a ruler. A scale and a north arrow were also added at this stage to allow compass readings to be added in the correct orientations.

The objective of this map was to record data on the locations, shapes, and lithology of many small exposures so these could be selectively added later to the field map. Exposures were added as outlines in the same way as in precision field mapping. To record their locations, two or three compass bearings to features that are present on the field map were taken. Triangulation using 2–3 bearings provides a useful way of finding a location and on small-scales can be more accurate than using

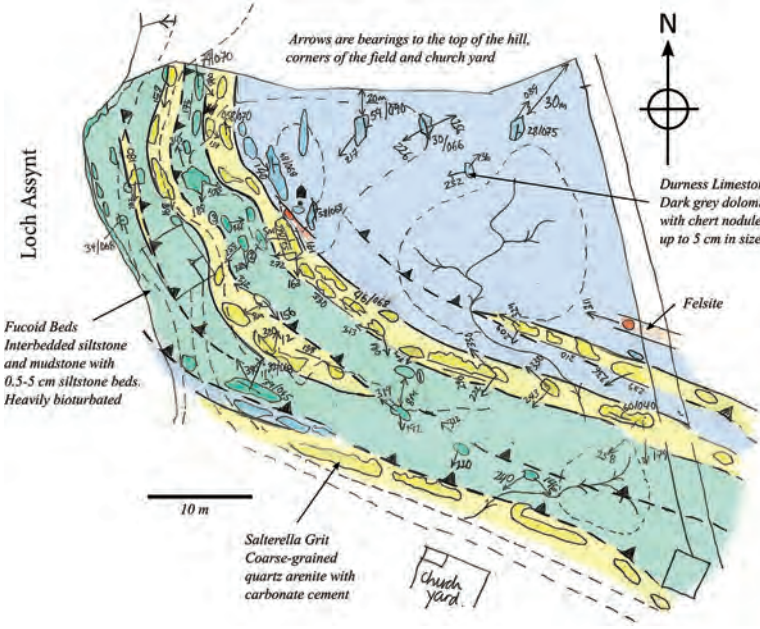
Arrows are bearings to the top of the hill, corners of the field and church yard
N
Loch Assynt
Durness Limestone
Dark grey dolomite with chert nodules up to 5 cm in size
Felsite
Fucoid Beds
Interbedded siltstone and mudstone with 0.5-5 cm siltstone beds. Heavily bioturbated
10 m
Salterella Grit
Coarse-grained quartz arenite with carbonate cement
Church Yard

Figure 13.5 A sketch map recording the outcrop pattern of mappable units at a higher scale than commonly used on basemaps.

a GPS—it also provides a means of plotting a location on the sketch map. The bearings were recorded directly onto the map for each exposure. In places counting paces was also used to measure the distance between exposures.

13.2.4 Sketch maps instead of field maps

When the objective of fieldwork is the investigation of specific localities, field maps may not be available. Occasionally it is not possible to obtain appropriate topographic maps because of local or national restrictions. Although aerial or satellite imagery can often be used in lieu of maps, these are difficult to use to clearly record data and can be illegal to possess in some countries. In areas of active geology, such as active volcanoes or active fault zones, maps may also not relate to current topography, owing to recent activity. Although aerial drones now provide a means of mapping topography to create maps (see Section 16.2), the data they collect requires significant processing that is not possible in the field.

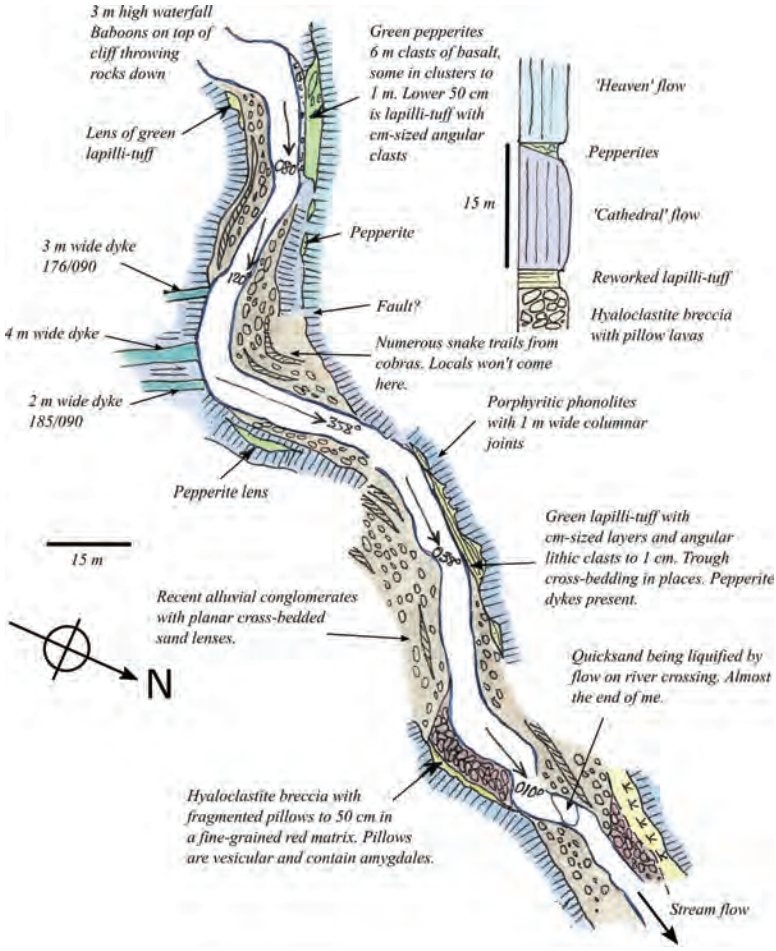
3 m high waterfall
Baboons on top of cliff throwing rocks down
Green pepperites 6 m clasts of basalt, some in clusters to 1 m. Lower 50 cm is lapilli-tuff with cm-sized angular clasts
'Heaven' flow
Pepperites
15 m
'Cathedral' flow
Lens of green lapilli-tuff
Pepperite
3 m wide dyke 176/090
Reworked lapilli-tuff
Hyaloclastite breccia with pillow lavas
Fault?
4 m wide dyke
Numerous snake trails from cobras. Locals won't come here.
2 m wide dyke 185/090
Porphyritic phonolites with 1 m wide columnar joints
Pepperite lens
Green lapilli-tuff with cm-sized layers and angular lithic clasts to 1 cm. Trough cross-bedding in places. Pepperite dykes present.
15 m
Recent alluvial conglomerates with planar cross-bedded sand lenses.
N
Quicksand being liquified by flow on river crossing. Almost the end of me.
Hyaloclastite breccia with fragmented pillows to 50 cm in a fine-grained red matrix. Pillows are vesicular and contain amygdales.
Stream flow

Figure 13.6 Sketch map showing the outcrops present along a ravine in the East African Rift in Tanzania.

Whatever the reason for the lack of maps, even accidental loss, a sketch map provides a means of recording much of the same information.

An example of a sketch map used in lieu of a field map is given in Figure 13.6. It shows a traverse along a ravine into the western escarpment of the East African Rift near Oldoinyo Lengai in Tanzania. Along the ravine were exposed a sequence of thick lava flows with thin horizons containing pillow lavas, hyaloclastite breccias, pepperites, and sparse

tuffs. The field relations suggest that thick lava flows dammed fluvial systems to generate transient lakes, resulting in phreatomagmatic interaction between water and the lava. The objective of the sketch map was to record the spatial relationships between the units and provided a rapid way to record information, which was required owing to safety concerns.

As a sketch of a ravine for which no maps were available, the river course and geology were recorded simultaneously during the traverse. At each bend in the river the topography of the river was sketched and a bearing of the trend of the river taken with a compass. Pacing enabled an approximate measurement of distance in lieu of GPS coordinates since the steep sides of the ravine prevented satellite acquisition.

Ravines are often difficult to map owing to their limited visibility and their tendency to be disorienting during a traverse. Measurements of the trend of river courses are useful even when maps are available. Labels were added to the maps during the traverse to record lithological and stratigraphic information, including some notes on safety aspects of the traverse. An approximate log of the sequence was created after the traverse was completed to summarize the important features of the stratigraphy.

13.3 Common mistakes

The most common mistakes in creating geological maps include the following:

- schematic exposure shapes (e.g. circles);
- symbols that are too small or poorly drawn;
- boundaries that are inconsistent with evidence from bedding measurements;
- poor use of boundary classification;
- use of irrelevant text annotations;
- structures not annotated with the proper symbolic annotations (e.g. fold axial traces).

13.4 Key concepts

In this chapter, several key concepts and methods were introduced:

- Sketch maps are useful to record spatial relationships at higher resolutions than field maps.

- Sketch maps are suited to areas with high degrees or exposure or scattered small exposures.
- Topographic features such as roads, rivers, and fences are useful to include to constrain the geometry of sketch maps.
- Position information should be recorded as GPS coordinates or through compass bearings and distances.
- Measurements and labels should be added directly to the sketch map.
- Peripheral field sketches with locations recorded on the sketch map provide an excellent means of recording detailed lithological, stratigraphic, and structural data.

14

Geological cross-sections

Creating and interpreting geological cross-sections are fundamentally important in Earth Science. The ability to project what is seen at the Earth's surface above and below ground is crucial in interpreting the structural evolution of the crust and the stratigraphic relationships between units. Every geologist, whatever their field, needs to be able to create cross-sections from geological maps and from their own field observations. Drawing cross-sections during fieldwork is also highly useful in interpreting the data already collected and in identifying where further evidence needs to be collected to better constrain the structure. Constructing approximate cross-sections in the field also has the benefit that, by the end of the fieldwork, the framework of the structure for the whole field area is already known.

Although cross-sections are two-dimensional slices through the geology of an area, they involve visualization of geological structures in three dimensions, because rarely are all the measurements and boundaries conveniently positioned along the line of section. Features that do not cross the line of section on the map can also appear on a cross-section since they project above or below the ground onto the section plane. Evaluating the three-dimensional surfaces represented by bedding, boundaries, faults, and folds is crucial in creating cross-sections.

In this chapter, the methods used in creating cross-sections from geological maps are described with a focus on the important features on maps that reveal the presence of structures. In the second part of the chapter, methods for generating sketch cross-sections within field notebooks will be discussed.

14.1 Cross-section techniques

Constructing geological cross-sections involves considering the intersection of geological structures with the landscape in three dimensions. An example of a simplified geological map is shown in Figure 14.1,

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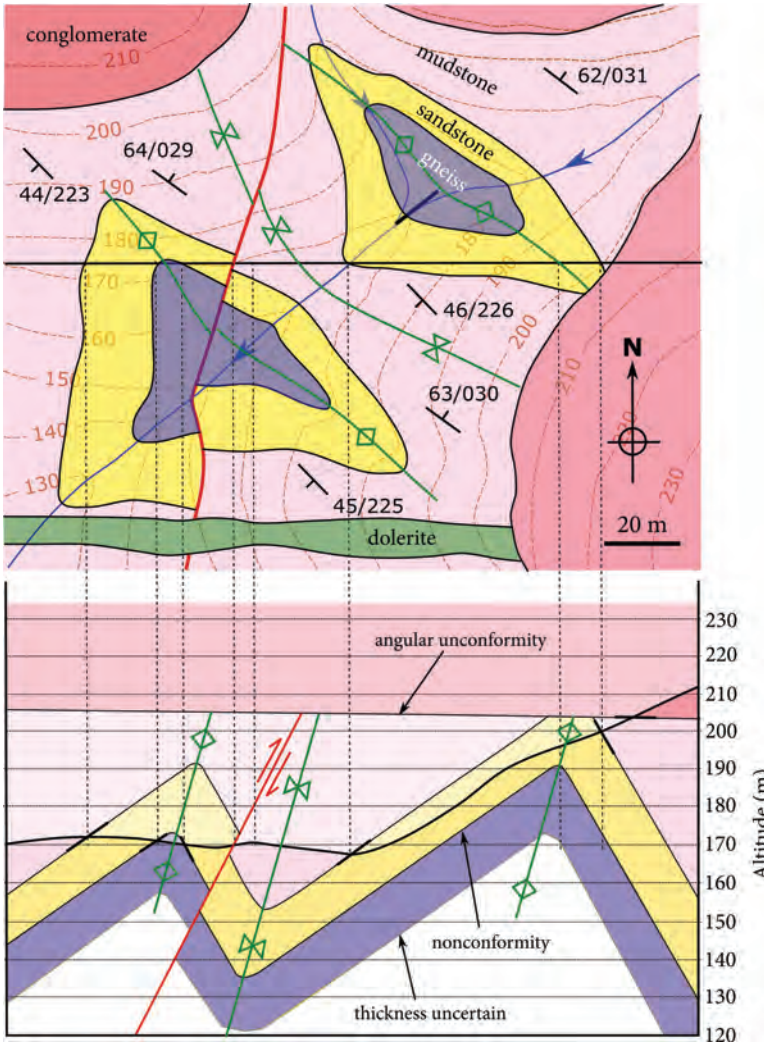

Figure 14.1 An example of a matching cross-section and map illustrating the methods and concepts used in creating cross-sections.

which illustrates many of the features that need to be assessed when creating a cross-section.

14.1.1 Interpreting the map

The very first task when creating any cross-section is to evaluate the geology shown on the map. This is crucial since an appropriate line of section needs to be chosen that will best illustrate the structures.

The first step in interpreting the map is to evaluate the topography. The contours need to be read to build a mental image of the landscape. In Figure 14.1 the contours show a valley running NE–SE with a stream running along it. A smaller gulley runs up the north side of the valley in the NE quadrant of the map. The contours are broadly equally spaced and form a pronounced V-shape at the river line, indicating the valley has near planar, steep sides.

The next task in interpreting the map is to assess the orientation of the boundaries between units and structures from their outcrop pattern. This is achieved by close inspection of the geometrical relationship between the contours, boundaries, and structures. On completely flat terrain deflections in the orientations of boundaries would indicate the presence of folds. On a landscape with relief, however, boundaries also change orientation owing to topography.

When a boundary crosses a contour its height at that position is the same as the contour line. Boundaries that are parallel to contours are, therefore, at constant height across the map and represent a horizontal plane. Here the base of the conglomerate unit runs nearly parallel to the contours except it moves down in height gradually to the east. The boundary is thus dipping at a shallow angle to the east. Notice that although the base of the conglomerate appears curved on the map, it doesn't represent a fold. The curvature is merely produced by the intersection of the boundary with the landscape. Since this boundary is near horizontal, and it caps all the hills, then it will appear all the way across the cross-section as the uppermost layer.

Boundaries that cut straight across contours with no deflection represent vertical planes. The dolerite dyke in the south of the map is thus vertical since it cuts straight across the valley. Intrusions often have somewhat non-planar contacts and thus may show some deflections. The dyke will not appear on the cross-section since it is parallel to the section plane.

Boundaries that cut contours and change orientation represent inclined planes. The boundaries between the sandstone and mudstone units form V-shapes on the map where they intersect the valley, indicating they are inclined. If this valley was U-shaped then the boundary would show a smooth change in orientation as it crossed the valley floor.

The dip of beds can be determined from the direction and shape of deflections in boundaries. The direction of the V into a valley points in the direction of dip, in this case towards the SW. Conversely, on ridges the V points in the opposite direction to dip. In this map the Vs indicate that the sandstone to mudstone boundary dips to the SW in the lowermost part of the map, but then it reverses and dips to the NE. There is, therefore, an antiform. The fold axial trace is shown on the map as a green trace, however, in many geological maps the trace will not be included, and folds will need to be identified from the outcrop pattern alone. The angle of the V-shape also relates to the dip of the beds. Sharp V-shapes indicate small dips, whilst open V-shapes indicate steeply dipping boundaries. In this case the shapes are more open to the NE and thus the folds have steeper limbs on the NE side.

Where boundaries deflect on maps to form V- or U-shapes that are not explained by the landscape (i.e. owing to valleys or ridges), they mark the location of fold hinges. The fold axial trace will connect the hinges of the fold from one boundary to the next.

In Figure 14.1 the sandstone unit forms an enclosed shape within the valley since the fold is upright (i.e. has a steeply dipping axial plane) and thus cuts through the valley. Assuming that the fold hinge is a straight line the hinges on either side of the valley can be connected to find the orientation of the hinge. This can be achieved for the antiform in the NE part of the map. The top of the V in the north of this structure lies at about 190 m height on the landscape, whilst the one in the south part of this structure lies at above 200 m. The hinge-line must, therefore, plunge at a small angle towards the NW, as shown in Figure 14.2.

There are two shapes enclosed by the sandstone unit, both representing antiforms. Between the two antiforms there must be a synform. Its fold axial trace is located where the mudstone pinches together. The shape of the fold can also be deduced by the outcrop pattern. The fold hinge is marked by a sharp deflection rather than a smooth curve, indicating these are chevron folds (see Section 4.1 on types of fold). The slopes of

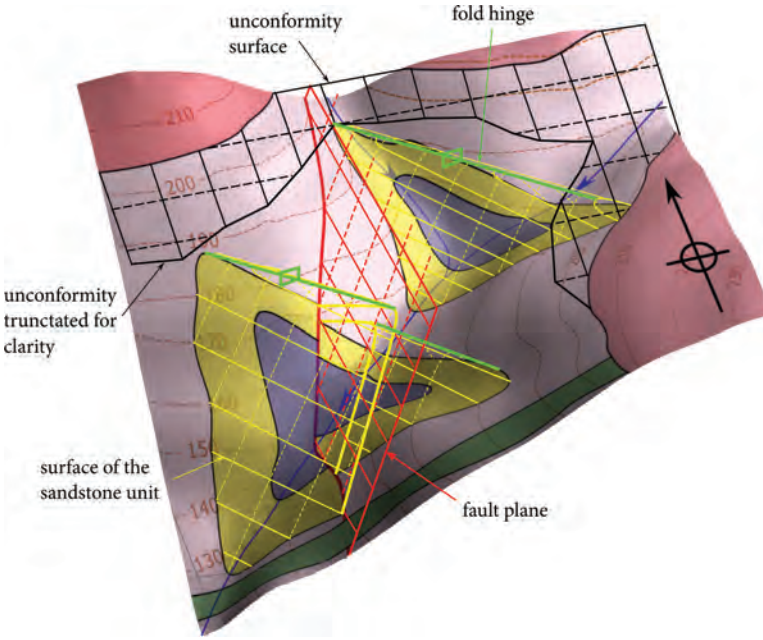

Figure 14.2 Showing the three-dimensional structure suggested by the map in Figure 14.1.

steep valleys often reveal the structure since they act as natural, if inclined and irregular, cross-sections.

The shape of the antiform also reveals another property of the appearance of units on maps—their apparent width changes with their dip. The width of the sandstone unit on the map changes across the fold and is wider in the SW than in the NE. The width of a unit on a map is not the same as the true thickness of the unit—it is an apparent thickness caused by the intersection with the landscape. On horizontal ground the true thickness (h) is related to the apparent thickness on a map (H) by

$$h = H \sin \theta \qquad (1)$$

where θ is the dip of the beds. The width of a unit on a map, therefore, can be used as a clue to its dip.

One more feature remains to be interpreted in the map. A fault cuts across the SW fold structure, causing a sudden displacement of the boundaries. The shape of the fault plane can be determined by the

trend of the fault trace on the landscape. There is an open V, pointing towards the west, in the fault trace as it crosses the valley. This indicates the fault plane is dipping at a steep angle towards the west.

The displacement on faults must also be determined to identify their type. In this case the fault truncates an antiform. Since these folds get wider downwards, the width of the fold structure will be less on the downthrown block. Inspection of the map shows that the distance between the sandstone–slate boundary is larger on the west, and smaller on the east. The downthrown block is thus on the east. Since the fault is dipping west, the eastern block lies beneath the fault plane and is the footwall. This allows the fault to be identified as a reverse fault (see Section 3.2 on the types of faults).

The map interpretation is now complete and a mental image of the three-dimensional structure of the area should resemble Figure 14.2. It has a series of upright chevron folds with axial planes dipping SW and hinges plunging at a low angle NW. The tops of the folds are cut off by a near horizontal unit of conglomerate.

14.1.2 Constructing the cross-section

Drawing the cross-section is straightforward once the map has been interpreted since the structure has been identified. The first task is to choose the line of section. In this case an east–west section line has been chosen. A line nearly perpendicular to fold and fault trends usually is the best choice to illustrate the structure. In complex areas, particularly those with superimposed folds, more than one plane of section may have to be used.

The next task is to create the topography profile line by transferring the contours from the map to the cross-section. It is usually best to draw cross-sections with no vertical exaggeration since the apparent dips of beds can be used to plot the boundaries. The best method to transfer contours is to align the edge of a piece of paper parallel to the line of section on the map and make a mark on the paper for each contour, labelled with the height. The marks on the paper can then be used to create a series of dots on the cross-section at the appropriate altitudes. Joining the dots allows the topography line to be generated, as shown in the lower half of Figure 14.1.

The boundaries, faults, and fold axial traces are now transferred from the map in a similar manner to the contours. These are marked on the topography line as short straight lines. The dips of the lines added are not the same as the true dips of the beds or faults on the map,

since the orientation of the line of section is at an angle to the dip of the beds. The angle of the boundaries and faults when viewed in the plane of section is an apparent dip (α) and can be calculated from

$$\alpha = \text{atan}(\cos\beta \tan\theta) \quad (2)$$

where θ is the true dip and β is the angle between the line of section and the dip direction of the plane. This apparent dip is always less than the true dip and becomes less as the angle between the dip direction and line of section increases. At an angle of 90° the apparent dip becomes zero. Since dip measurements are usually not present exactly on the line of section, those considered most representative can be extrapolated along their strike to the section line.

An approximate apparent dip can be obtained without calculation using a notebook page and a pencil. The apparent dip can be observed by holding the notebook in the same orientation as the plane (e.g. bedding) and then drawing the line of section onto the page. The notebook merely needs to be viewed perpendicular to the cross-section plane to see the apparent dip of the pencil line.

Boundaries are always extrapolated above and below the landscape in cross-sections. The best method to achieve this is to initially draw straight lines parallel to the apparent dips. In the current case this works well because the folds are chevron folds with straight limbs. With rounded folds the dip changes along the limb and the straight lines will need to be amended to curves. The best way to estimate the shape of folds in a cross-section is using the outcrop pattern and bed thickness. If the outcrop suggests the folds are chevrons then unit thickness is likely to be constant around the fold. Likewise, open rounded folds tend to exhibit relatively constant unit thickness. Tight and isoclinal folds with inter-limb angles of less than 30°, in contrast, often exhibit thickening of units in the hinge region that are most prominent for incompetent units such as mudstones, slates, phyllites, or schists. Competent units such as limestones, sandstones, and quartzites tend to exhibit far less thickening at hinges and can also generate cusp-like fold shapes. A good guide to the geometry of larger folds is to examine the shapes of minor folds seen in the field. It is useful to use measurements of the plunge of folds to project the height at which a hinge will intersect the plane of section. An easy approximate method to achieve projection is to hold a pencil in the same orientation as the fold hinge and observe the height that it intersects the section plane.

Cross-sections will often require some degree of interpretation to complete since they are a best guess model of the structure. The interpretation that agrees with the most evidence is the one that should be used. Interpretations should also be added as labels to cross-sections. Here there are three important interpretations. Firstly, the conglomerate unit cuts across the fold axial planes with a constant shallow dip. The base of the conglomerate, therefore, is an angular unconformity. Next, the sandstone unit overlies a metamorphic slate and the boundary between the two is also an unconformity (see Section 9.1). Finally, the fault is cut by the dolerite intrusion, whilst the intrusion is cut by the unconformity. The faulting, therefore, proceeds the intrusion, which was followed by erosion and deposition of the conglomerate. All these features can be labelled in the cross-section.

The final task is to ink-in the cross-section and to add colour. The same colours as the map should be used; however, it can be good to emphasize the topography line by making colours above the ground slightly lighter. The level of uncertainty in boundaries can also be indicated by using different line styles for constrained and inferred boundaries. In this example the boundaries are all well constrained by the map. Annotations such as fold axial traces and the sense of movement of faults should also be added.

14.2 Sketch cross-sections

Geological cross-sections prepared from maps are interpretations of structure extrapolated above and below ground that are usually tightly constrained by evidence from the map. During fieldwork, in particular during mapping, cross-sections can be drawn to convey ideas and to test models on the structures being mapped. These cross-sections can be considered to be sketches and are less technical than those created from completed maps. Two types of sketch cross-section can be used in the field to help develop structural models: cross-sections that represent a small-scale structure of one or more outcrops in close proximity and cross-sections that summarize a large-scale structure that often combines data obtained over several days.

14.2.1 Small-scale sketch cross-sections

Figure 14.3 shows an example of the use of small-scale cross-sections to interpret structure. It relates to several adjacent localities in northwest Scotland. The localities represent a traverse on a single bearing where the

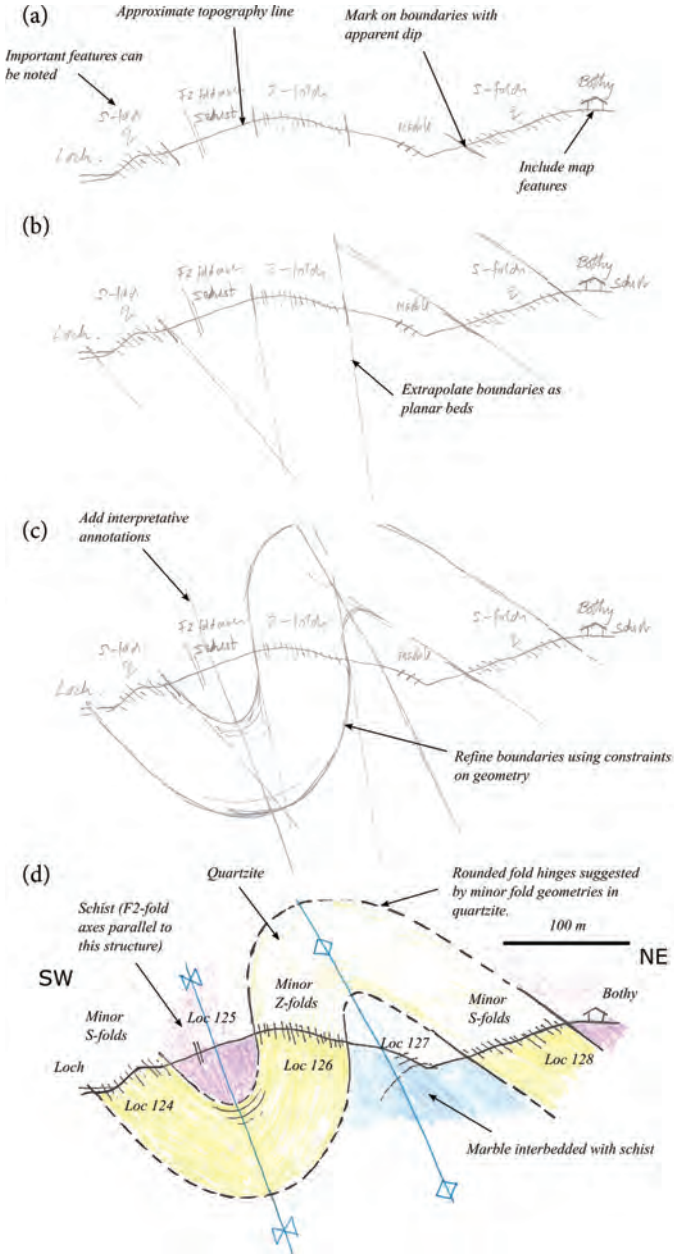

Figure 14.3 A sketch cross-section of a series of localities in northwest Scotland.

change in bedding and the repeat of lithology suggests a fold. The objective of the sketch cross-section is to identify the geometry of the fold.

Small-scale sketch cross-sections are usually created in the field immediately after a series of localities have been recorded. They represent a summary interpretation of those localities an in a notebook and do not need a specific locality number—although it is advisable to ensure they are clearly marked as a summary interpretation. Sketch cross-sections are often drawn straight after walking over, or whilst still looking at, the landscape. The topography line can, therefore, be approximated rather than drawn technically from contours. The apparent dips of the beds at each locality and the boundaries between them can then be estimated rather than calculated. The notebook method of apparent dip can be used if uncertain (Section 14.1.2). It is often useful to draw a series of strokes for bedding across an outcrop to reinforce bedding orientation.

This qualitative approach to a cross-section is obviously subject to some error, but often for small-scale features the error is small enough that the exercise provides valuable insights into the nature of a structure. The value of the sketch is increased by including locality numbers and any landmarks along the line of section. Labels and annotations should be added to the sketch. Since these diagrams are interpretative in nature their format is less rigorous than field sketches or logs, consequently labels can include raw ideas and questions.

Good uses for small-scale cross-sections include evaluating: (1) the throw on faults and their geometry, (2) the geometry of fold structures, (3) variations in the thickness of units, (4) cross-cutting relationships on scales larger than a single outcrop, and (5) the geometry of unconformable surfaces. Often a series of small-scale sketch cross-sections will save considerable time when creating cross-sections of an area from a completed map.

14.2.2 Large-scale sketch cross-sections

A large-scale sketch cross-section has more in common with those prepared from a map and is designed to synthesize data from a large number of localities. Typically, these sketches will be made whilst mapping, but not whilst in the field, however, they remain interpretative sketches rather than technical drawings of the structure. Several large-scale sketch cross-sections can be made in a notebook on a particular area showing the evolution of ideas on the nature of structures present.

An example of a large-scale sketch cross-section is given in Figure 14.4 and shows a series of localities in Assynt in northwest Scotland. In these

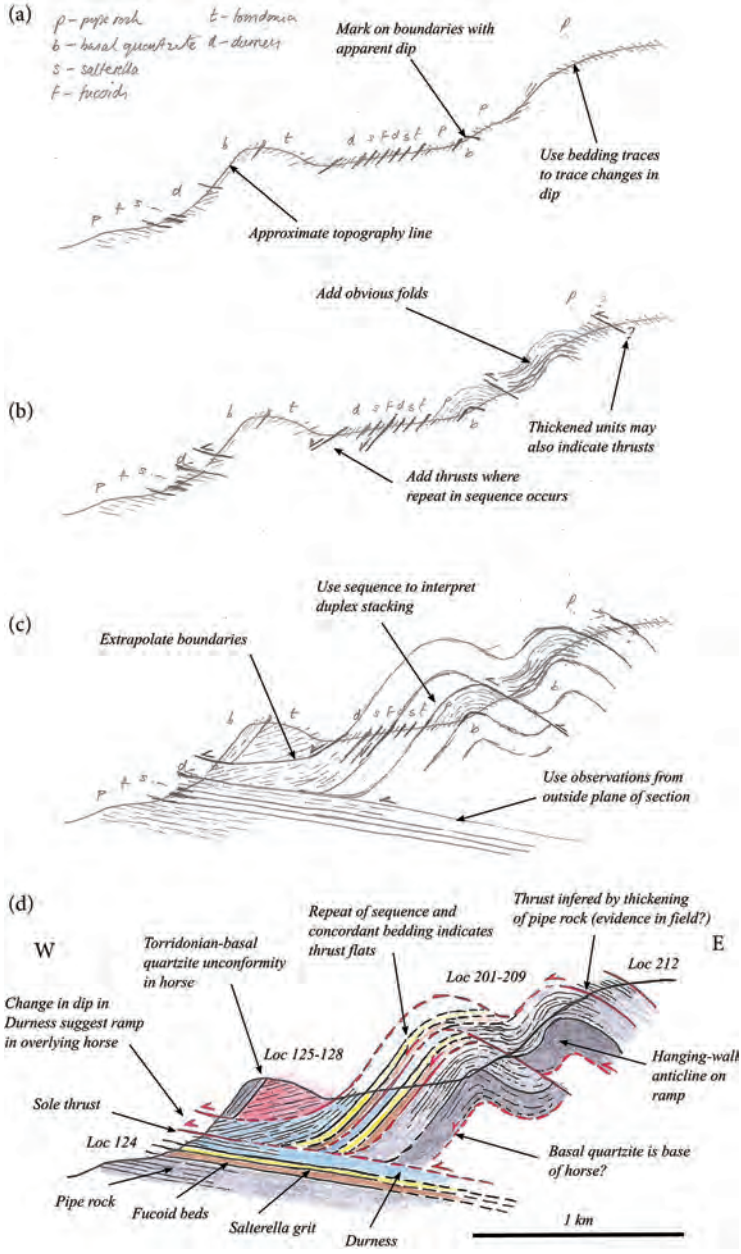

Figure 14.4 A large-scale sketch cross-section through an area in Assynt in northwest Scotland.

cross-sections the topography line often has to be drawn by reference to the contours on a topography map, although it isn't necessary to transfer these accurately, with some practice it is possible to draw a reasonably accurate topography line simply by noting where the slope is steep or gentle and where valleys and ridges are located.

The dip of beds and boundaries are marked on using an approximation of their apparent dips. In this case there are many units, thus labels and a key were used to prevent confusion whilst drawing. Faults in Assynt are very rarely observed, despite the excellent degree of exposure, consequently at first none are added as observations to the landscape line shown in Figure 14.4a.

Next, simple interpretations can be made, and this usually involves knowing the general style of deformation. The structure in this part of Assynt consists of thrust duplexes comprising stacked horses of rock bound by thrusts. In the horses hanging-wall anticlines can be present. Thrusts can be parallel to bedding on sections of the thrust known as a flat, or at an angle of 60° to bedding where they cut up through the sequence on ramps.

Interpreting the structure of this cross-section depends on locating the thrust faults. The nature of thrust duplexes shown in Figure 14.5 illustrates that thrusts occur where the sequence repeats or is truncated and where there is a sudden change in orientation of the bedding by 30° or 60°. Care has to be taken to distinguish between hanging-wall

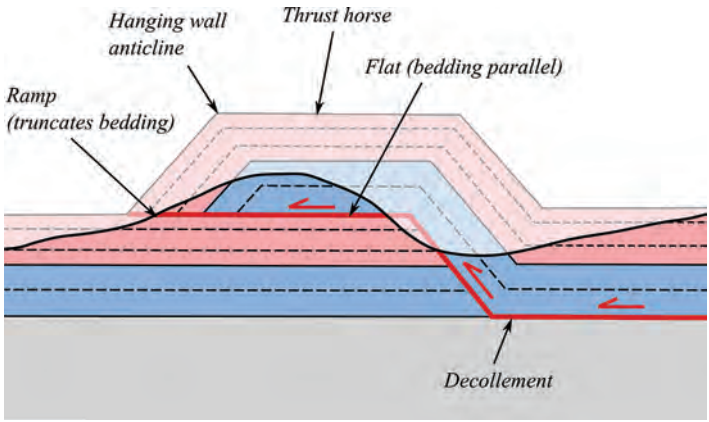

Figure 14.5 Illustrating the structure of a thrust duplex and its intersection with landscape.

anticlines and changes in bedding orientation owing to thrusts. In this cross-section several hanging-wall anticlines can readily be interpreted by the smooth change in bedding. The location of thrusts can also be inferred.

Extrapolating the structure above or below the landscape can be achieved through trial and error by attempting to find the simplest possible structure compatible with the style of deformation. Uncertainty can be indicated in the cross-section using dashed boundaries. It is useful in this diagram to include lines that represent bedding within units since it allows the presence of thrust ramps to be seen clearly.

The addition of labels, colour, and scale completes the sketch. Labelling with locality numbers helps relate this interpretation to the other field notes. Some indication of the line of section, such as map coordinates should also be given.

14.3 Common mistakes

14.3.1 Topography line structure

The most common mistake made in cross-sections is to align structures with the topography line, in particular fold axial planes. This tendency probably originates from the misconception that structures are unconstrained above the topography, whilst in reality the geology outside the plane of section is likely to provide constraints. The cross-section shown in Figure 14.6 is a typical example of where the topography line is assigned a special significance that it does not have. The fold geometry in the section has been distorted in an attempt to make this interpretation seem feasible.

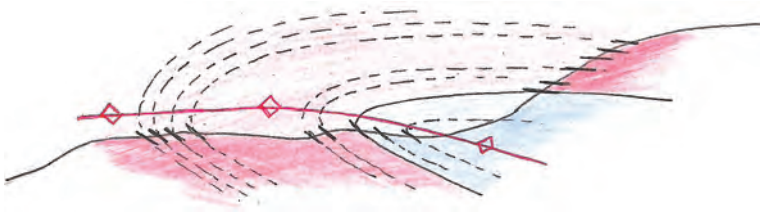

Figure 14.6 Showing the common mistake of using the topography line as a structural surface.

14.4 Key concepts

In this chapter, several key concepts and methods were introduced:

- Sketch cross-sections are a useful means to test interpretations of structure.
- Topography lines can be sketched with reasonable accuracy rather than transferred from maps.
- Transfer boundaries and bedding orientations as in regular cross-sections.
- Extrapolate boundaries and structures above and below the landscape to test models of the structure.
- Use labels to record interpretations and questions—these can be useful in identify targets for further investigation.

15

Drawing schematic diagrams

Not every diagram in a field notebook will be a sketch of something that was observed. Some diagrams will be schematic illustrations of hypotheses used to develop interpretations. Schematic diagrams are useful since they provide a means of visualizing complex spatial relationships that are sometimes not easily achieved using just imagination alone. They are also very useful in communicating interpretations to others. In teaching schematic diagrams are invaluable visual aids to understanding that can summarize complex concepts in a form that is easy to digest. Likewise, schematic diagrams are valuable in illustrating interpretations in scientific papers or reports. Although scientific consensus should be evidenced-based and impartial, reaching consensus involves debate and discussion. Schematic diagrams allow a hypothesis to be presented in its clearest possible form to enable the most convincing presentation of ideas.

Drawing schematic diagrams is more difficult to do well than creating field sketches. Drawing a field sketch requires the ability to record the relevant features and thus involves sketching what is seen. In contrast, schematic diagrams involve drawing from the imagination and an ability to think spatially is important. Whilst field sketching depends on the ability to see a three-dimensional scene as a two-dimensional image, drawing schematic diagrams involves the opposite skill, to imagine three-dimensional surfaces and then translate them to the page. The methods used in creating schematic diagrams vary depending on the type of diagram.

15.1 Block diagrams

Block diagrams are perhaps the commonest schematic diagram used in Earth Science since they can be used to show the intersection of structures through several surfaces or the relationship between a landscape and the subsurface. These diagrams involve drawing a three-dimensional

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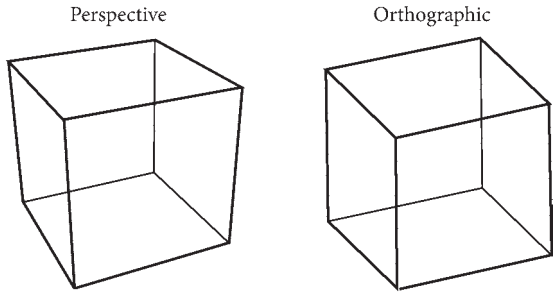

Figure 15.1 Illustrating the difference between perspective and orthographic projections of a cube.

rectangular block onto which structures or landscapes are superimposed.

There are two approaches in drawing block diagrams: perspective or orthographic. In a perspective view those features further from away from the observer are smaller; scale decreasing with distance from the viewer. In an orthographic view features remain the same scale irrespective of distance. These two views are illustrated in Figure 15.1. Although a perspective view is more realistic, an orthographic view is easier to construct since opposing sides of the block are parallel and of the same length. The human brain is good at interpreting three-dimensional images and orthographic representations are sufficient to create the impression of depth, albeit with an awareness that the view is somewhat unnatural.

Adding features to a block diagram involves imagining their intersection with each of the faces of the block, which takes practice. A useful way to learn the skill is draw the intersections of faults and folds onto a plain cardboard box and then draw it from different angles. After doing this exercise several times it should be easier to draw structures from the imagination.

15.1.1 Structure block diagrams

An example of a block diagram used to illustrate the three-dimensional relationships between tectonic structures is shown in Figure 15.2. It illustrates the superposition of three generations of fold structures. The first stage of construction is to draw a box, in this case a cube, with each side of the same length, and opposing edges consisting of parallel lines. To add the fold structures to the faces of the cubes, the fold axial planes should be drawn first as guides for the geometry of the beds.

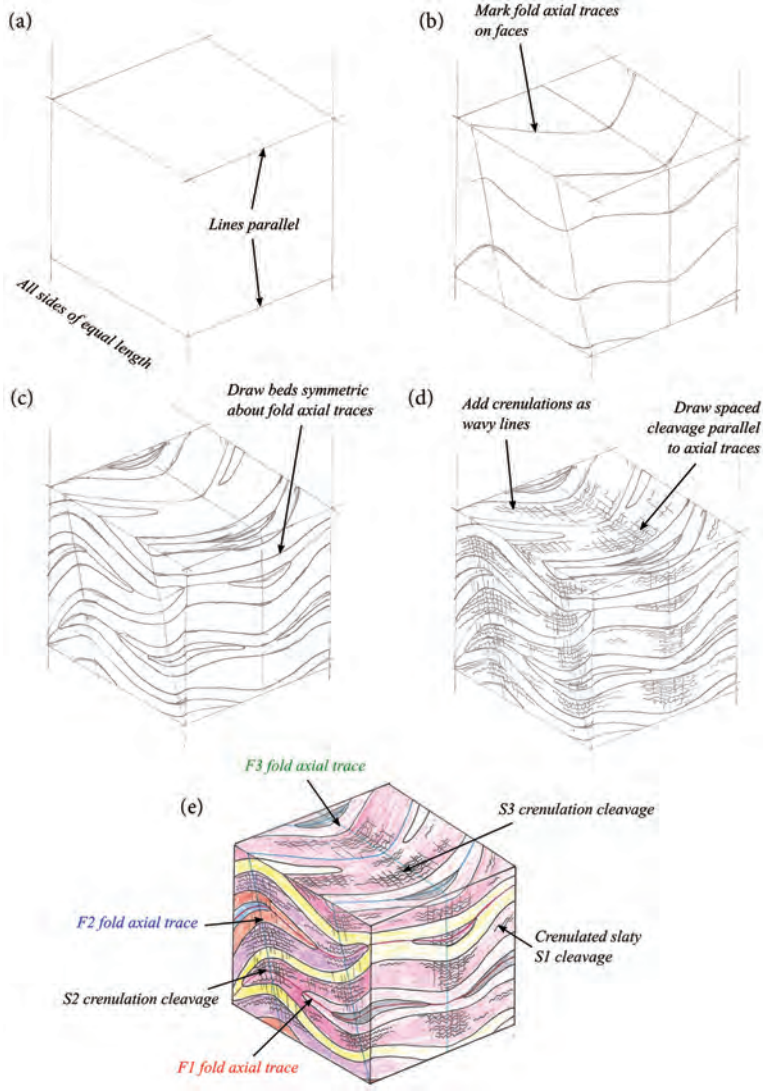

Figure 15.2 An example of a structural block diagram illustrating the interference of three generations of fold.

A fundamental concept in drawing the traces of the fold axes is that the earlier folds are deformed by the later folds. It is, therefore, easiest to start by drawing the axial trace of the last phase of folding (here F3) since these will be straight-lines on the surface of the block. The next oldest fold axial traces (here F2) can then be drawn and will curve around F3 axial traces. The earliest fold axial traces will be deflected where they cross any later fold axis, as shown in Figure 15.2b.

Adding beds to the diagram is achieved by following each bedding trace along the faces of the cube by recognizing that the lines will sweep in towards a fold axis along their length, cross the axis, and then sweep back away from it. The bedding will be symmetrical about the fold axial traces, as shown in Figure 15.2c. At this stage in drawing much erasing and repositioning of lines occurs to ensure the folds have a realistic geometry.

Once enough beds have been drawn the diagram is essentially complete since it adequately illustrates the geometry of the folds. In this case, however, slaty and crenulation cleavages have also been added to increase the value of the diagram. Each generation of cleavage is drawn parallel to the corresponding fold axial surface, with crenulations drawn as sinusoidal lines. The addition of colour and labels completes this drawing.

15.1.2 Landscape block diagrams

The second major use of block diagrams is in illustrating the relationship between landscape and the underlying geology. An example of a landscape block diagram is shown in Figure 15.3 and illustrates sedimentation within piggy-back basins within a fold thrust belt.

Often in landscape block diagrams a rectangular block will be used as a base rather than a cube. Drawing the block can be achieved using a ruler and ensuring that opposing edges are parallel and of equal length, as shown in Figure 15.3a.

In adding the landscape to the block diagram guidelines can be drawn on the side faces of the block that are parallel to the edges and represent lines of equal altitude. These guides ensure that the intersection of the landscape with the side faces of the block can be drawn relative to the horizontal. To add the landscape, its line of intersection with the side-faces is drawn first (Figure 15.3b). This step is most easily achieved by consulting reference images of the type of landscape to be drawn, either photographs or using Google Earth. Usually significant vertical exaggeration must be used to ensure features are easily visible in block diagrams.

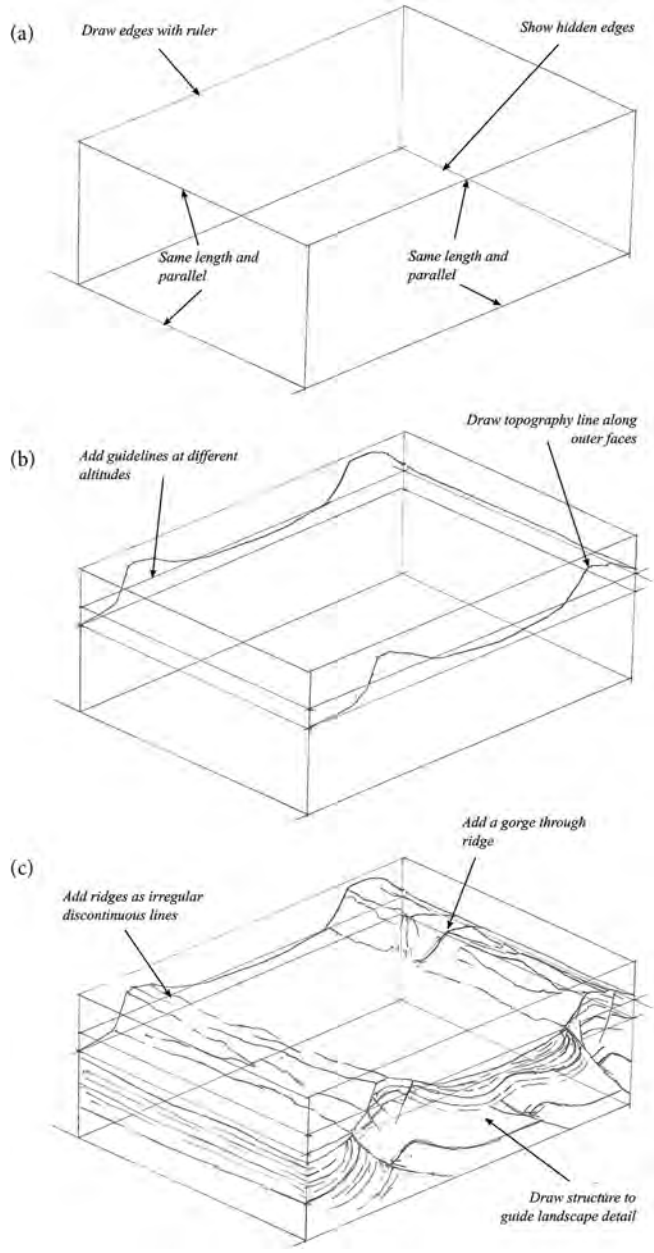

Figure 15.3 Initial stages of drawing of a block diagram illustrating a piggy-back basin.

Once the landscape line has been drawn it is often useful to draw the sub-surface structure onto the side-faces of the block. The sub-surface geology, whether a structure as in this case, or a sedimentary sequence, often controls the features to be drawn on the landscape surface. In this diagram the structure consists of several thrust ramps with hanging-wall anticlines. The thrusts are located on the foreland-side of the ridges in the landscape formed by hanging-wall anticlines. Between the hanging-wall anticlines and the thrusts are piggy-back basins containing sediments, as shown in Figure 15.3c. Often reference images, such as cross-sections, greatly assist in drawing the sub-surface geology realistically. Particularly important in this respect are the syndepositional folds within the sedimentary cover in the piggy-back basins.

Drawing the landscape surface involves creating the impression of a three-dimensional surface with the minimum number of lines. A good method is to draw ridge-lines and the upper margins of other topographic highs to block in areas of high and low topography on the landscape. In this sketch ridges are drawn along the tops of the mountains formed by the hanging-wall anticlines as sub-parallel irregular lines. To show the steep, foreland-facing cliffs, which often appear on ridges in fold thrust belts, the lower boundary of the cliff face has also been drawn, as shown in Figure 15.3c. A gorge is also added through one of the ridges by drawing lines that denote the upper margins of its cliffs.

Detail can now be added to the topographically low areas of the landscape. The trace of meandering rivers and tributaries are drawn through the piggy-back basins. The orientations of the rivers are chosen to be sub-parallel to the edges of the block diagram to give the impression of a sub-horizontal surface. An alluvial fan emanating from the gorge cut through one of the ridges has also be drawn as a rounded outline with numerous river channels fanning outwards across its surface. This feature has been added to illustrate the formation of fanglomerates by a change in sediment routing. Short vertical lines are also added to the cliffs to reinforce the impression of slope. Some bedding traces are also drawn on the cliffs to illustrate the underlying structure.

The final stage of the diagram is to add colour and labels. In this case colours have been enhanced with subtle shading to convey the three-dimensional nature of the surfaces. Adding darker colours to areas where significant changes in slope occur, such as close to the rivers or

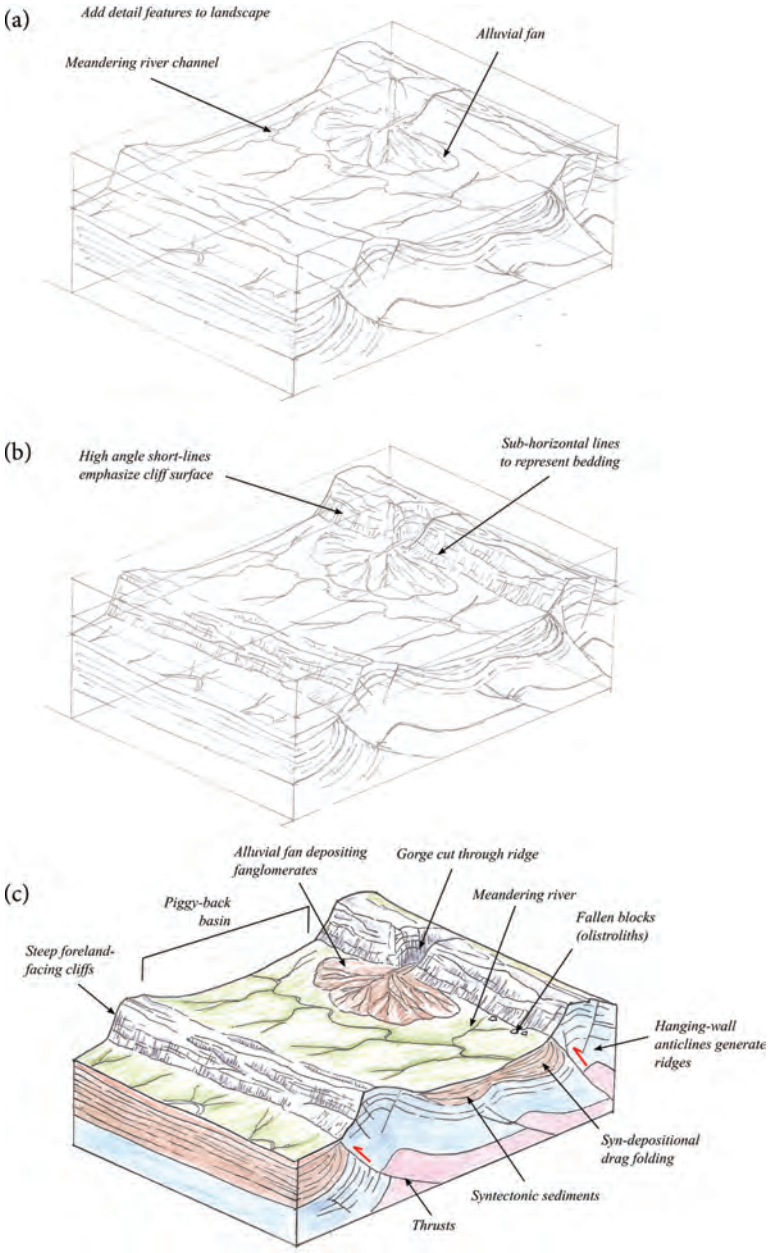

Figure 15.4 Final stages of a drawing of a landscape block diagram.

at the base of the cliffs generates natural looking shadows, as shown in Figure 15.4c. Annotations have also been added to show the sense of movement on the thrusts.

15.2 Surface section diagrams

Surface sections are similar to structure block diagrams except they show one or more marker beds in three dimensions to illustrate structure, rather than the intersections of structures with the faces of a block. Surface sections are highly useful in illustrating superimposed fold structures, as shown in Figure 15.5.

Drawing a surface section begins in a similar way to structure block diagrams with construction of a box. The fold axial planes are then added to the faces of the box as in Section 15.1, however, their intersection with all faces of the block, including background faces is included, producing the impression of a transparent three-dimensional curved surface, as shown in Figure 15.5a.

Next, a marker bed is drawn. The intersections of the bed with the faces of the block are drawn first, including back faces, then the upper and lower surfaces marked on as horizon lines. The drafting of these lines follows the same procedure described in Section 15.1. Often at this stage lines must be erased and repositioned in order to generate a realistic structure (Figure 15.5b). The presence of so many lines makes it difficult to visualize the three-dimensional shape and some simplification will greatly improve the clarity of the diagram. Often making the marker bed opaque, so that it obscures lines and structures behind it, gives a better impression of its three-dimensional shape. To achieve this, the lines hidden by the bed are erased, as shown in Figure 15.5c. To enhance the three-dimensional nature of the marker bed, surface features can be added. In this case two sets of joints were added as short, discontinuous lines, as shown in Figure 15.5d.

The final stage of drawing is to ink-in, add colour and labels. Colour, in particular, improves the clarity of this diagram significantly by differentiating between the different fold axial surfaces. Subtle shadows added to the lower surface of the marker bed also enhance the impression of a three-dimensional surface. The completed diagram is shown in Figure 15.5e.

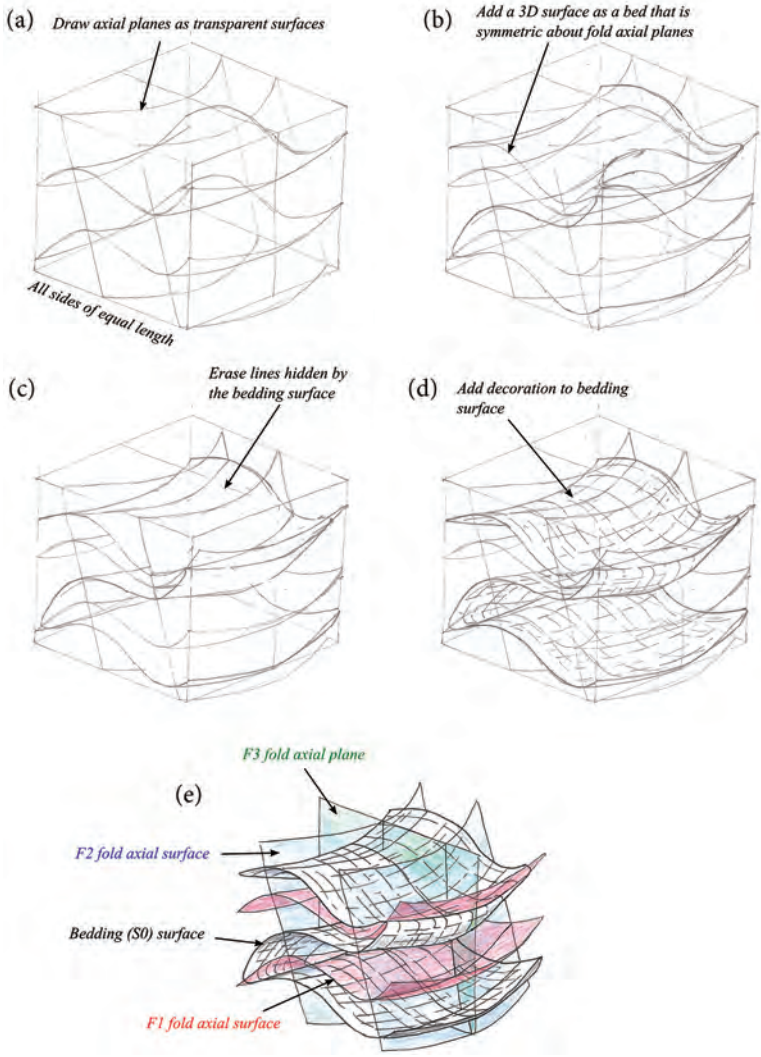
(a) Draw axial planes as transparent surfaces
All sides of equal length
(b) Add a 3D surface as a bed that is symmetric about fold axial planes
(c) Erase lines hidden by the bedding surface
(d) Add decoration to bedding surface
(e)
F3 fold axial plane
F2 fold axial surface
Bedding (S0) surface
F1 fold axial surface

Figure 15.5 A worked example of a surface section diagram illustrating three generations of superimposed fold.

15.3 Process diagrams

Schematic diagrams can also be used to illustrate processes to help test the validity of interpretations. These diagrams have no set form but tend to show an evolving time sequence of events. Labelling with the

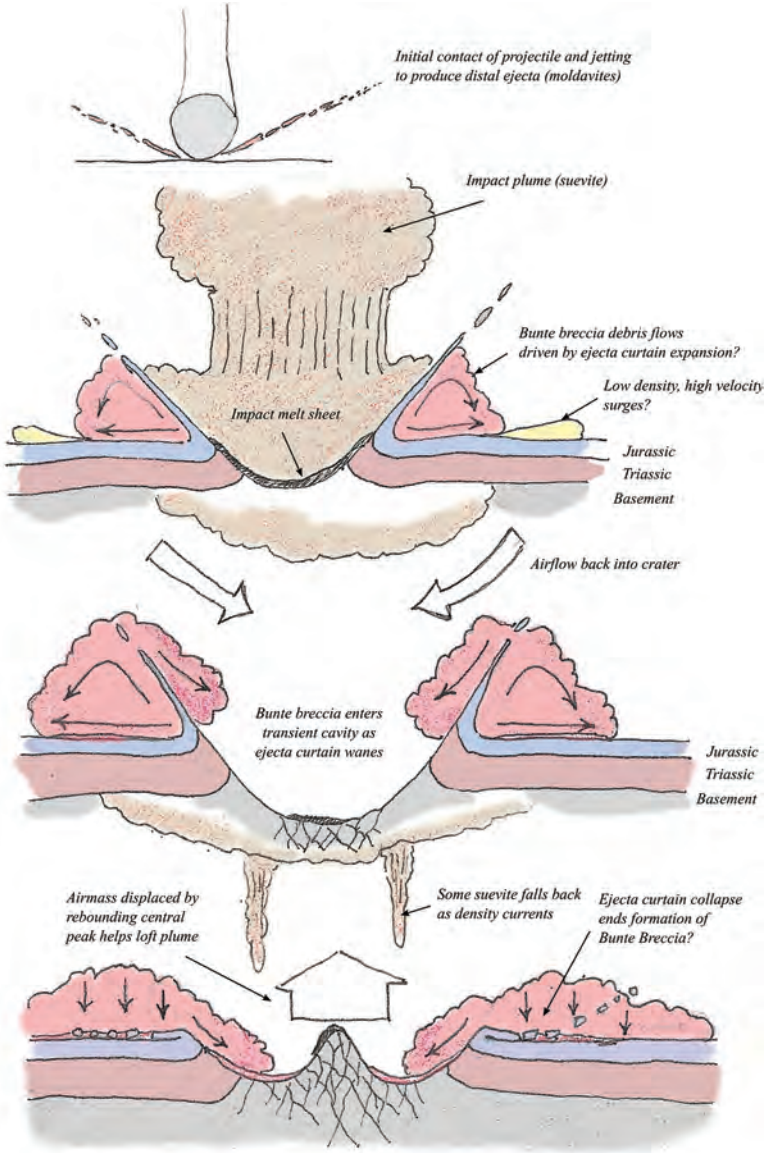
Initial contact of projectile and jetting to produce distal ejecta (moldavites)
Impact plume (suevite)
Bunte breccia debris flows driven by ejecta curtain expansion?
Low density, high velocity surges?
Impact melt sheet
Jurassic
Triassic
Basement
Airflow back into crater
Bunte breccia enters transient cavity as ejecta curtain wanes
Jurassic
Triassic
Basement
Airmass displaced by rebounding central peak helps loft plume
Some suevite falls back as density currents
Ejecta curtain collapse ends formation of Bunte Breccia?

Figure 15.6 An example of a process diagram showing an interpretation of the formation of Reis Crater in Germany.

key requirements and conditions for the processes assists in the evaluation of their likelihood. They are very much a storyboard for a scientific mechanism.

An example is given in Figure 15.6 and shows ideas on the formation of Reis impact crater in Germany. The diagram was created in a notebook as part of a summary of all observations made during a fieldtrip to the crater. The objective of the diagram was to record and test interpretations made in the field. In particular the sketch examines the timing of the formation of the cavity of the impact crater and the emplacement of the different ejecta layers present at Reis Crater. The evolution of the crater is followed as a series of time steps.

A wide range of process diagrams can be used in interpretative sections of field notebooks to illustrate the evolution of models. Process diagrams can show the progressive formation of complex structures, the mechanisms of intrusion of igneous bodies, the chemical evolution of magmas though crystal fractionation and crustal assimilation, or the change in a sedimentary environment. Any problem that can be illustrated pictorially can be investigated with a process diagram.

15.4 More examples

Examples of schematic diagrams are shown in Figure 15.7 to illustrate their diversity. Figure 15.7a and b are both block diagrams from field notebooks used in summarizing field interpretations. Figure 15.7a shows an interpretation of palaeoenvironment of Triassic siliciclastic sediments containing potential vertebrate trackways from Sardinia and shows the position of tracks on the surface and in the sub-surface relative to transverse and longitudinal bars within braided river deposits. Figure 15.7b shows a block diagram illustrating the internal structure of the stratovolcano Kerimasi in Tanzania. The diagram was constructed on the basis of several traverses along ravines up the volcano and along the lower slopes.

Schematic diagrams used in communicating Earth Science concepts in undergraduate teaching are shown in Figure 15.7c to e. All three diagrams are designed to illustrate the relationship between melt generation, tectonics, topographic features, and the nature of volcanism in a simplified manner. They illustrate (c) the mid-Atlantic ridge, (d) the East-African rift, and (e) the lesser Antilles subduction zone. All the diagrams were created within a graphics application as described in

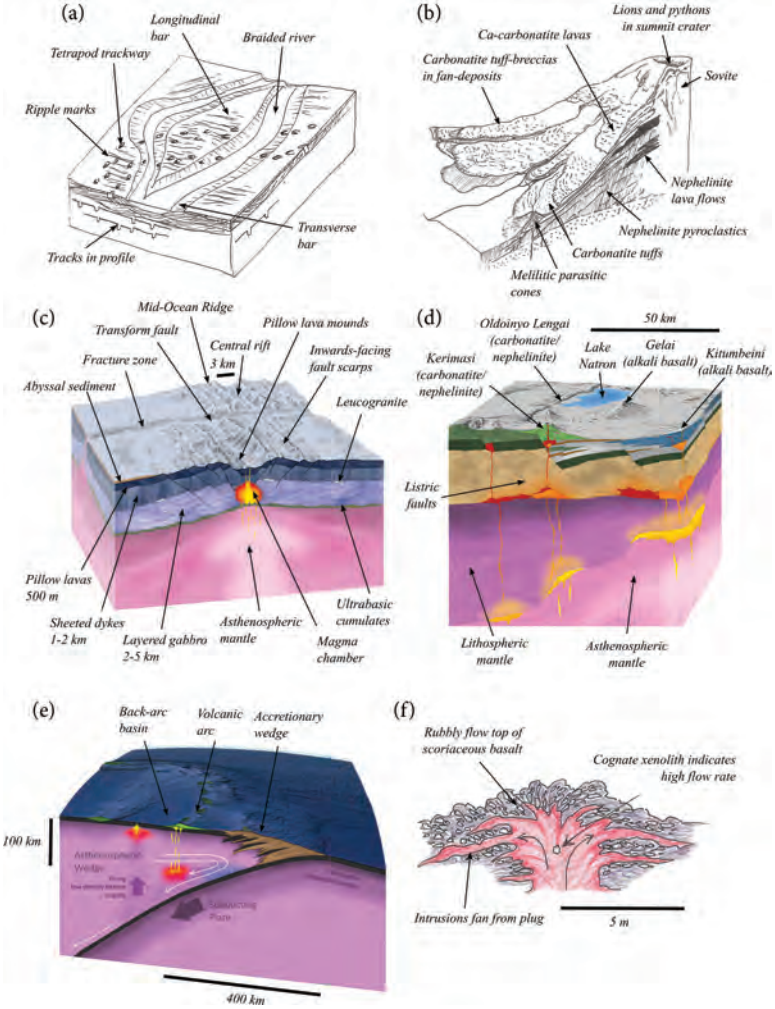

Figure 15.7 More examples of schematic diagrams used as both interpretative aids and for illustration of concepts.

Chapter 16. The topography in the diagrams of Figure 15.7d and e was obtained from Google Earth. In Figure 15.7d, the topography was over-painted with colour.

Finally, a process diagram from a field notebook is given in Figure 15.7f. The diagram shows the intrusion of magma into the flow top of an Aa

lava flow on Mount Etna and was created to illustrate an interpretation within a fieldwork summary.

15.5 Key concepts

In this chapter, several key concepts and methods were introduced:

- Schematic diagrams are useful for illustrating and developing interpretations.
- Schematic diagrams can and should be included in field notes.
- Block diagrams can be used to illustrate structures and environments.
- Process diagrams represent a cartoon of interpretative thoughts.

16

Modern techniques in illustration and recording in geology

Advances in technology have enabled new methods in the acquisition and recording of field data in geology and its presentation within publications. These techniques do not replace field drawings; however, they do provide opportunities that field sketches do not. Modern technology also enables the digital manipulation of images and the construction of illustrations that are essential in the preparation of publication-ready diagrams for reports and scientific papers.

16.1 Photogrammetry

A relatively new technique in Earth Science to record the features of a specimen or a rock face uses photographs to generate a three-dimensional (3D) computer model. The technique is termed photogrammetry and requires no special equipment or skills to achieve.

Photogrammetry works by matching features between photographs taken at different angles in order to define the 3D coordinates of the surface. To create a 3D model it is necessary to take a series of images around a specimen, or across a rock face, at a wide range of different angles. Photographs can then be uploaded into photogrammetry software to generate a model rendered using a texture generated from the images. Digital photographs that record direction and position, such as those taken with a smartphone or modern camera, can be used to create models. Some photogrammetry software is freely available online and is limited merely by the number of images that can be used.

The limitations of photogrammetry include those of photography in general. Deep shadows and reflections often cause issues in generating 3D models and resolution is limited to the number of pixels in photographs. The resolution issues associated with photography usually mean it is impossible to confidently identify either minerals or rock types.

Geological Field Sketches and Illustrations: A Practical Guide. Matthew J. Genge, Oxford University Press (2020).
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Two examples of 3D models generated by photogrammetry are shown in Figure 16.1. The first shows as small-scale feature within an ignimbrite where fiamme are surrounded by a cavity formed of vesicles. This 3D model was constructed from 27 photographs taken at different angles surrounding the structure. The second example shows a volcanic bomb from Santorini in the Aegean. The bomb has broken into two pieces on impact with the ground and produced a bomb sag—a depression of layering within the existing volcanic deposits. This model was constructed from only 15 images. The location of the outcrop also limited the variations in photograph direction. Both models can be viewed from any direction in the imaging software.

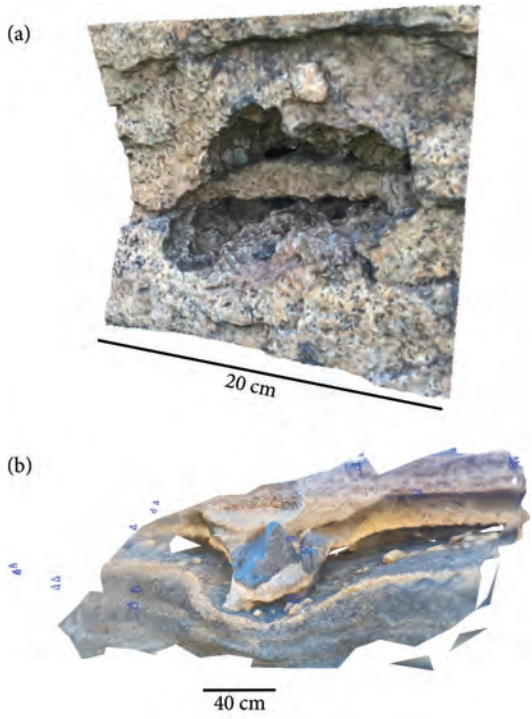


Figure 16.1 Examples of 3D textured models created by photogrammetry. Images show (a) a fiamme structure from an ignimbrite in Sardinia and (b) a volcanic bomb sag from Santorini. Camera positions are shown for the bomb sag.

16.2 Aerial drone surveys

Aerial drones with global positioning systems can be used to generate 3D models, orthomosaics, and digital elevation models of exposures via photogrammetry. The best drones for such surveys are those capable of flying double grid flight paths to ensure sufficient coverage of the landscape being mapped. Some drones are capable of automatically flying such missions and it is only necessary to define the grid to be mapped, often on a tablet connected to the drone. Less capable, and cheaper, drones have to be flown manually and sufficient photograph coverage can be less easy to achieve. Manual flight paths can also be used to collect imagery of vertical exposures, such as cliff faces. Processing of aerial drone images involves similar steps to photogrammetry and requires appropriate software. Several free online options are available but often limit output and resolution. Local laws need to be observed when using drones and in some countries a permit is needed to operate them.

An example of a drone survey of Monte De Fiore, a scoria cone on Mount Etna erupted in 1974, is shown in Figure 16.2. The survey was obtained using a Phantom 4 drone with an automated mapping flight path set to cover the entire area. The drone control software allowed the boundaries of the survey area to be defined on a tablet connected to the drone. Altitude, together with camera resolution, determines the resolution of the survey, in terms of the number of pixels per unit area. The lower the altitude, the better the resolution, however, the smaller the total area that can be covered with the available flight time. In this case an altitude of 50 m was chosen with 80 per cent overlap between images taken on parallel traverses to enable optimal height resolution from photogrammetry. Variable topography results in differences in resolution, and more importantly in coverage. Here the drone base station was established on the highest point on the rim of the cone to ensure images had sufficient overlap for successful construction of the 3D model. The survey took 15 minutes to complete and incorporated 250 images.

The results of the survey can be exported as a 3D model, orthomosaic aerial image, or a digital height model. The survey thus provides an excellent means of recording geomorphological features of the cone, such as the inwards dipping vent facies deposit in the crater and the lava flow that dissects one side of the edifice. The digital elevation model can also be used to extract volumes for the cone and lava flow providing

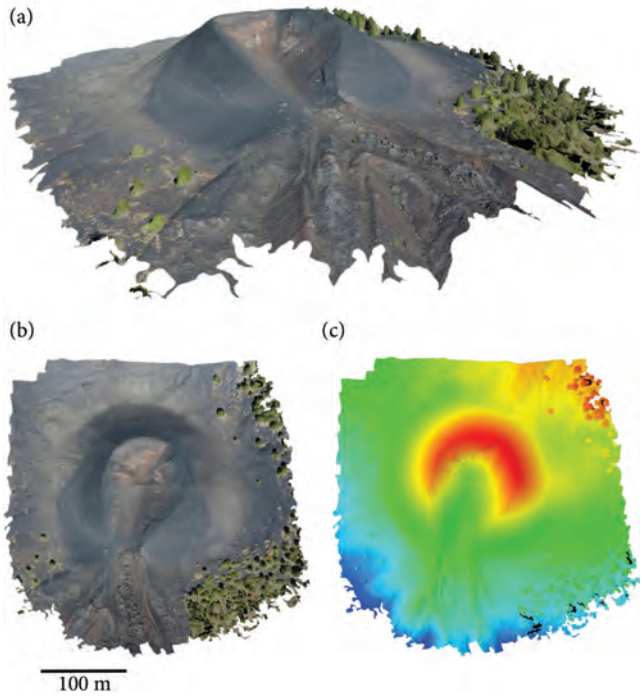


Figure 16.2 An aerial survey of one of the two scoria cones comprising the 1974 Monte De Fiore flank eruption on Mount Etna. Images show (a) a 3D construction, (b) an aerial orthomosaic, and (c) a colour coded digital elevation model.

constraints on the volume of magma erupted. Lithological information, however, cannot be obtained and the survey is most valuable when combined with traditional field observations.

16.3 Quantitative image analysis

Data such as the size and abundance of specific components of rocks can be obtained quantitatively from digital images. Size distributions of crystals within igneous rocks or clasts within sedimentary rocks can provide important constraints on the sorting processes that operate during their transport or, in the case of igneous and metamorphic rocks, the nature of their growth. The ability to extract quantitative data from photographs provides constraints that are more rigorous than semi-quantitative observations.

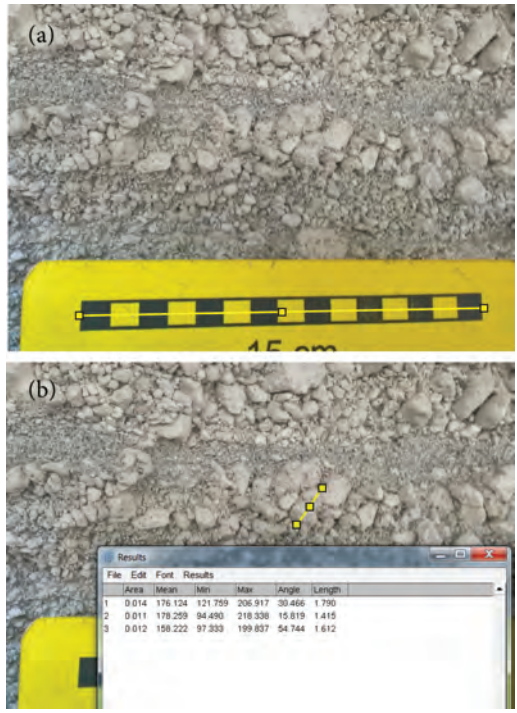


Figure 16.3 Showing steps involved in measuring the dimensions of objects in ImageJ. First (a) the scale is measured using the line tool, then (b) the size of each object is measured using the line tool.

ImageJ is the leading image analysis software used in science and benefits from being a free application. The software can be used to measure sizes and abundances both manually and semi-automatically. An example of manual size measurement is shown in Figure 16.3 for a pumice lapilli-tuff from Santorini in the Aegean.

The method for measuring sizes in ImageJ requires a scale be present in the imported image. The length of the scale is entered by adding a line object to the image using the line tool on the main ImageJ toolbar (Figure 16.3a). The size of the scale is specified in the menu shown under Analyze>Set Scale. Successive measurements can then be made manually by drawing with the line tool. The length of each line is obtained by selecting Analyze>Measurement (or pressing Ctrl+M). Each measurement is then added to a list that can be saved later as a file. Using

manual measurements, the apparent size of objects in an image can be measured quickly.

As well as manual measurements ImageJ also includes automated methods to measure sizes, shapes and abundances of objects based on colour or tone thresholding. These methods involve selecting the colour range of a component within an image. Often thresholding results in poorer results than manual selection, however, in images where components can be distinguished adequately, the software provides a useful way of obtaining large amounts of data quickly. There are numerous tutorials online describing the different measurement techniques available in ImageJ. Like any measurement technique, nevertheless, the error involved in the analysis must be determined. Repeat measurements provide a means of evaluating the precision (repeatability) of the data and are usually presented as a standard deviation.

16.4 Publication-ready diagrams

Hand-drawn field sketches are rarely used in scientific papers or reports. Instead annotated photographs or line drawings produced using drawing software are used. Although not field recordings these are essential tasks for an Earth Scientist.

16.4.1 Image processing

Photographs taken in the field often suffer from issues with contrast related to light conditions. The ideal conditions in which to take photographs are with indirect lighting in which no deep shadows occur, for example, when the weather is overcast. The least favourable conditions are in direct bright sunlight with directional shadows. Unfortunately, ideal lighting conditions are rare, particularly within tropical and subtropical locales, and insufficient field time is usually available to wait for conditions to become optimal. Digital photographs can, however, be processed with software to minimize the obscuring effects of shadows.

Several different techniques can be used to improve the appearance of digital images. The simplest technique involves changing the brightness and contrast of an image, however, this usually results in unnatural-looking photographs with overly bright areas. Brightness and contrast can also be manipulated using curve tools where the brightness of pixels in a certain tonal range can be adjusted. Although superior to simple global brightness and contrast change, the results often

produce images where pixel depth (colour resolution) is significantly impaired. The final method to fix issues with deep shadows is compositing, where two versions of an image, one over- and the other under-exposed, are combined to generate a final corrected image.

An example of an image with deep shadows is shown in Figure 16.4a. The photograph shows tuff from Santorini with low angle cross-lamination and is likely to represent a surge deposit, however, the shadows obscure the laminations and limit its use in a report or publication. This

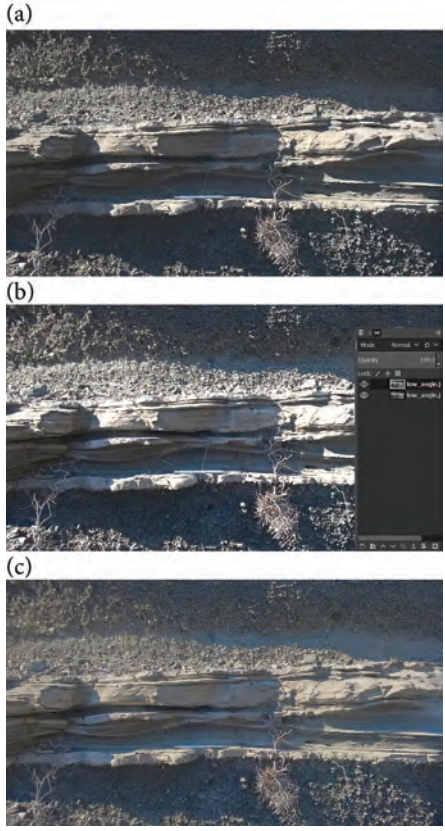


Figure 16.4 Digital processing of an image to minimize the obscuring effects of shadows by compositing. Images show: (a) the original photograph of low angle cross-laminations within a pyroclastic base surge deposit, (b) the enhanced brightened layer prior to removal of bright areas, and (c) the composited final image.

picture can be corrected using compositing in image processing software. Numerous software applications are available, however, in this example the program Gimp will be described since it is free to use.

Correcting the photograph involves creating two copies of the image in Gimp on two separate layers. Most image processing software includes the concept of layers that contain different elements of the final picture. In Gimp the layers are shown in the layer rollout on the right sidebar, as shown in Figure 16.4b. When opened the picture will consist of a single layer—a second can be created by right clicking on the layer in the list and selecting the Duplicate command. Compositing involves increasing the brightness of the dark areas of the image and combining them with the unaltered image. To increase the brightness of the shadowed areas, select the upper image layer in the list and go to Image>Brightness-Contrast on the top menu. Adjust the brightness and contrast sliders in the menu until the shadowed areas are sufficiently bright and resolved, as shown in Figure 16.4b.

To combine just the darker areas of the upper image layer with the lower layer it is necessary to remove the bright areas. These can be selected from Select>By Color and left clicking on an area of the image to choose the colour to select. The threshold value shown in the select menu allows a range of colour to be selected around the chosen value. In this case a value of 100 was used. Finally, invert the selection using Select>invert.

The last task is to make the bright areas of the upper layer transparent, so the lower layer shows through. This is achieved by adding a layer mask under Layer>Mask>Add Layer Mask—ensuring that the option 'Selection' is chosen in the Add Layer Mask menu. The image is now complete and can be saved. The final product is shown in Figure 16.4c and shows a much flatter image where the shadows are much less prominent.

Image processing software such as Gimp is also useful in correcting colour issues with photographs by changing the hue and saturation of images. Photographs often do not accurately record colours owing to variations in light temperature caused by weather conditions and time of day. Sometimes colour is a sufficiently important property to require adjustments to be made.

16.4.2 Line drawings

Line drawings include field sketches, schematic diagrams, logs, or maps. Producing publication-ready line diagrams involves the use of a vector drawing program. The application Inkscape is an excellent choice, not only is it free, but it is also feature-rich and easy to use.

An example of a line drawing using Inkscape is shown in Figure 16.5. A reference image has been imported as a guide for the lines and the line tool (Figure 16.5a) is used to trace over the reference image in a series of short straight lines by left clicking to add nodes. The best results are achieved by adding more nodes where the line curves. To convert the line from straight-line segments to a continuous curve, select the entire line using the node selection tool on the side toolbar (Figure 16.5b) and the select the curve button on the top toolbar (Figure 16.5c). Sections of the line can be adjusted individually by selecting nodes and using the Bezier curve handles. Dragging the handles will modify the curve, as shown in Figure 16.5d.

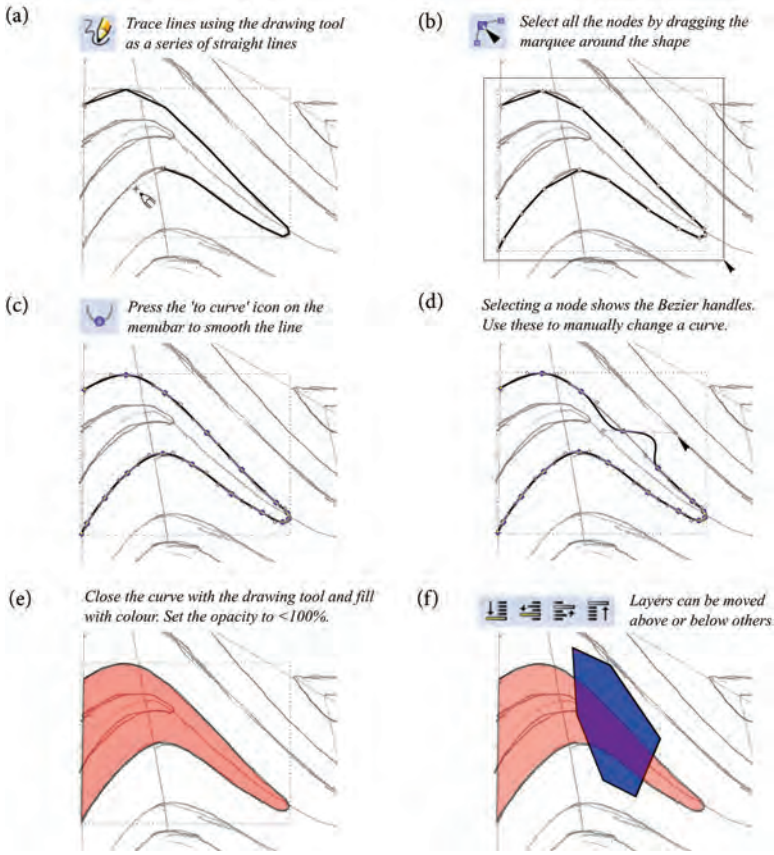

(a)
Trace lines using the drawing tool as a series of straight lines
(b)
Select all the nodes by dragging the marquee around the shape
(c)
Press the 'to curve' icon on the menubar to smooth the line
(d)
Selecting a node shows the Bezier handles. Use these to manually change a curve.
(e)
Close the curve with the drawing tool and fill with colour. Set the opacity to <100%.
(f)
Layers can be moved above or below others

Figure 16.5 How to create line drawings using Inkscape.

Some line drawings will benefit from areas of colour to create more complex schematic diagrams. Most of the schematic diagrams used in this book were created in Inkscape. To create areas of colour the regions enclosed by lines can be filled by selecting the line and choosing a fill colour from the palette at the bottom of the screen. Right clicking the palette allows either the fill or line (stroke) colour to be changed—lines can also be hidden completely by selecting the no stroke colour. Often it is best to apply fills to shapes entirely enclosed by a line since this determines the area to be filled more accurately.

Layers are useful when applying colour to line drawings. Each line and shape within a drawing is created on a new layer located above the last one added. Fill colours can be opaque or transparent. To make a fill transparent the opacity value should be set to less than 100 per cent in the Fill and Stroke menu (present in the list on the right-hand side of the screen). The effect of transparency will depend on the level of a layer in the drawing. The layers will be rendered in order into the final image, one on top of each other, and thus the order is important.

An example of the effect of layering is shown in Figure 16.5f in which a blue shape with an opaque fill has been drawn after the transparent red shape. When the level of the blue shape is higher than the red shape it will obscure the underlying layers. The level of layers can be adjusted by selecting a shape with the Object Select tool and using the level adjustment buttons in the top toolbar. Moving the blue shape below the transparent red shape produces the effect shown in Figure 16.5f. Often when creating complex diagrams much adjustment of levels is required to achieve the desired result.

Working with large numbers of objects is usually required in creating complex images. The block diagram shown in Figure 9.1, for example, consists of more than 100 separate objects. Grouping objects together allows manipulation of several different objects at the same time and is useful in repositioning them or changing their level. Objects are grouped by selecting them, by dragging around them with the Object Select tool (the uppermost tool on the left toolbar), or by left clicking them whilst holding down Shift, then choosing Object>Select.

Many of the concepts used in hand-drawing, as described throughout this book, are useful in electronic line drawing. Line-thickness, for example, can be used to emphasis certain features, colour emphasizes the spatial relationships between areas, and shadows and highlights can also be created using areas filled with slightly lighter darker colours

(c.f. Figure 4.1). Using line drawings within publications greatly improves the clarity of the science that is presented and is worth the additional time spent in creating high quality illustrations.

16.4.3 Annotation of photographs

Photographs are usually used in publications as evidence. Often in photographs lithological and structural features are less easy to identify than they are in the field and annotations are required to highlight them. Annotations include lines, areas, and labels and can be added to photographs in a range of software; however, Inkscape is particularly useful. An example of an annotated photograph is shown in Figure 16.6 and illustrates the sequence within the deposits of the Minoan eruption of Santorini.

A key consideration when adding annotations is that they should merely enhance features and make them easier for the reader to identify, not obscure detail. Line widths must be chosen on the basis of the reproduction scale of the image so they can easily be seen but do not cover features. Line colour is also important and depends on the colours

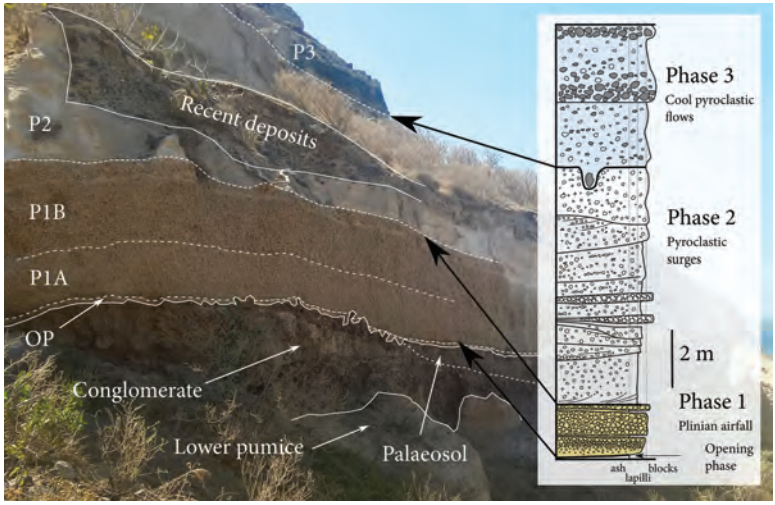


Figure 16.6 An example of an annotated photograph illustrating the volcanic sequence of the Minoan eruption of Santorini. Abbrev: OP—opening phase, P1—phase 1, P2—phase 2, P3—phase 3. The figure also illustrates the use of a schematic log to highlight elements of the image.

already present within the photograph. Areas can also be highlighted with colour. To ensure these do not overly obscure detail they can be assigned a transparency, so the underlying features can still be seen. Finally, when producing a composite figure, consisting of several photographs, always label each component image with a letter that will be referenced in the figure caption (e.g. Figure 1 Lithological features of the study area. (a) Clasts within the basal conglomerate. . .). Any abbreviations used within labels on the image should also be explained within the figure caption.

16.4.4 Digital image painting

Schematic diagrams, in particular block diagrams used for illustration of concepts, can benefit from the incorporation of textural elements that represent geological features such as crystalline textures or fabrics. Digital painting can be used to create textures within diagrams, often together with vector drawing software. Some examples of block diagrams in which painting has been used are shown in Figure 15.7.

Many image processing applications such as Photoshop and Gimp allow painting of colour using brushes that can be used to generate realistic looking diagrams. The process involves adding colours to different layers of the diagram using a selected brush. Often soft brushes are useful where the colour intensity decreases from the centre to the edge of the painted area producing a gradational colour. Digital painting uses many of the same concepts as traditional painting. First base colours are added to block-in important areas on one or more layers, then detail is added in overlying areas, often with a textured brush which paints using a pattern. Frequently using a transparent layer for the addition of detail results in a more realistic appearance. Layers can then be modified using adaptive tools such as a smudge or blend brush to enhance the natural appearance of the texture. Finally, small-scale details such as areas of deep shadow along fractures or beds, or specular highlights can be added to increase the realism of the painting.

An example of a digitally painted texture that could form part of a block diagram is shown in Figure 16.7 and was created using Gimp. The image was generated by painting a series of folded beds in different colours using a diffuse brush onto a black background to form a base colour. A new layer was then created, and speckles of light and dark colour were added randomly over the image using a speckle brush (Figure 16.7b). The speckles were then smeared out using a smudge tool

with short strokes parallel to the bedding to create the impression of random layering (Figure 16.7c). The two layers were then merged and a warp tool used to generate smaller deflections in the layering parallel to the fold axial planes to produce minor folds on a range of scales (Figure 16.7d). The image was still rather flat, so highlights and lowlights were painted along the top and bottom of the beds using a small elliptical brush. Some highlights were also added inside some beds. The painted lines were then smoothed with the smudge tool. Finally, the merged image was duplicated into four layers, cut into pieces, and moved to produce displacements resembling faults. The fault lines were decorated by painting thinner dark lines, smoothed with a smudge brush.

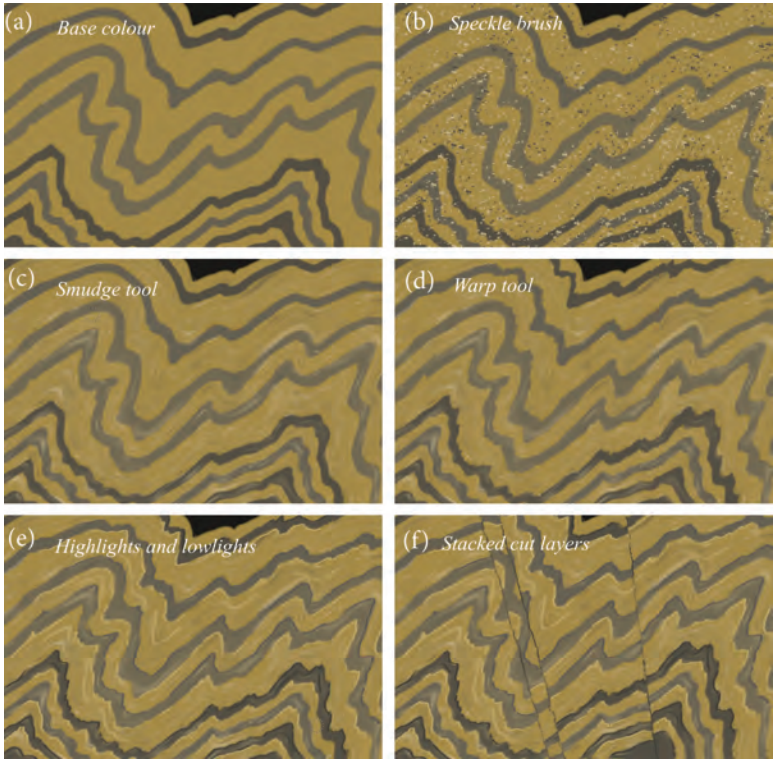


Figure 16.7 An example of digital painting to produce a diagram of folds cut by sub-parallel faults.

Digital painting is a highly useful technique in creating schematic diagrams. The best results are obtained through experimentation. A steep-learning curve is associated with using many digital painting applications.

16.4.5 Three-dimensional models for illustration

A powerful technique for generating illustrations of complex 3D objects, such as landscapes, is to create a model using 3D graphics software. There are many 3D applications available to create such models, however, a leading free application is Blender and allows professional looking illustrations to be created.

An example of creating a projection of a 3D model of a landscape of O'ahu in the Hawaiian Islands is given in Figure 16.8 and is textured with a geological map. To create the landscape a height map of the topography is required in which the altitude of each position is denoted by greyscale colours as shown in Figure 16.8a. In Blender a grid object was used as a mesh to which the height map was applied and can be added to the scene under Create>Grid in the left-side toolbar. The number of required subdivisions in the X and Y direction is set in the panel and should be less than the number of pixels in the height map.

The height map is applied to the grid using the Displace modifier. To use this, select the object and open the height map image under Texture>New>Open in the right properties panel, as shown in Figure 16.8b. The modifier can now be applied by selecting the modifier panel and choosing Displace. The displace modifier needs the imported height map to be selected. Pressing Apply will set the heights of vertexes in the mesh according to the greyscale colours in the height map.

Usually when an object, such as a landscape, is created using a height map its vertical scale will be significantly exaggerated (Figure 16.8c). The scale tool can be used to change the vertical height of the object by selecting the object in Object Mode and pressing S followed by Z and then dragging with the mouse.

The created landscape is shown in Figure 16.8d and has a pixelated appearance since the quads that make up the surface are planar. A shader can be applied to smooth the edges of the quads. To apply a shader, select the object and go to Edit Mode (lower toolbar). The landscape should be selected and is highlighted (if not press A). On the right toolbar select the shader tab and press the smooth button.

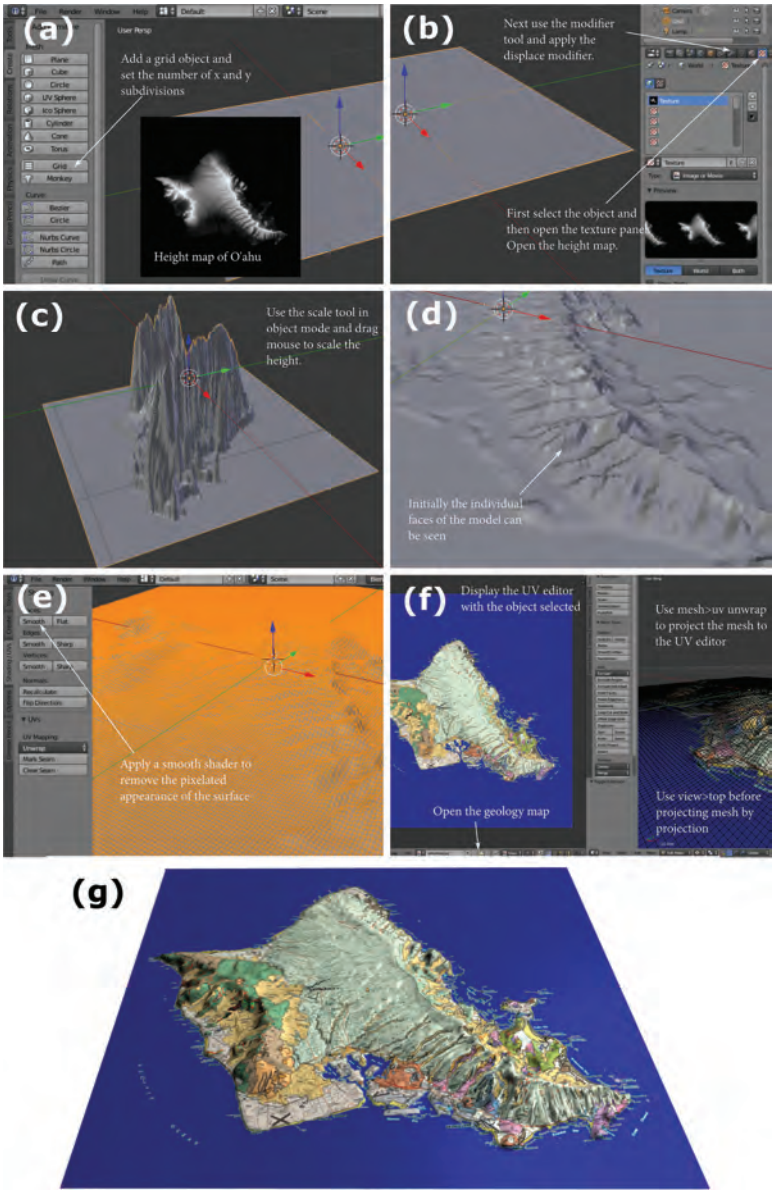

(a)
Add a grid object and set the number of x and y subdivisions
Height map of O'ahu
(b)
Next use the modifier tool and apply the displace modifier.
First select the object and then open the texture panel. Open the height map.
(c)
Use the scale tool in object mode and drag mouse to scale the height.
(d)
Initially the individual faces of the model can be seen
(e)
Apply a smooth shader to remove the pixelated appearance of the surface
(f)
Display the UV editor with the object selected
Use mesh>uv unwrap to project the mesh to the UV editor
Open the geology map
Use view>top before projecting mesh by projection
(g)

Figure 16.8 Illustrating the construction of a 3D geological map of O'ahu using Blender.

The final stage of generating the model is to apply a texture. In this case a geological map will be projected onto the landscape. The map texture needs to match the features of the height map in order for the geology to be displayed in the right position. This can be achieved in an image processing program such as Gimp by opening the height map and geological map as two separate semi-transparent layers and rescaling the layers until they match. The geological map can then be cropped and exported as a file.

Applying a texture to a 3D model is achieved by UV mapping and it is necessary to set the texture coordinates of each vertex in the grid object (Figure 16.8f). In Blender this is achieved in the UV editor, which allows the UV texture to be unwrapped graphically and a projection of the mesh overlain on the texture. The process of UV mapping in Blender is the subject of many online tutorials and is straightforward and so will not be explained here. Once complete, the object can be viewed in Blender using the textured view setting (bottom toolbar). The image can be exported either by rendering or simply using a screen shot. The final version of the 3D geological map is shown in Figure 16.8g. This technique was also used to create the image in Figure 14.2.

16.5 Key concepts

In this chapter, several key concepts and methods were introduced:

- Photogrammetry and aerial drone surveys can be used to complement traditional field notes.
- Image analysis software is useful in obtaining quantitative data from scaled photographs.
- Publication-ready diagrams involve digital drawing and painting using graphics software.
- Photographs for use in publications should be corrected to ensure optimal contrast and brightness.
- 3D design software can be used to create schematic diagrams.

APPENDIX A

Geological field notes

Field sketches and schematic diagrams are an important component of good field recordings; however, on their own they do not provide sufficient information to record geology. Diagrams must be accompanied by written notes. Good field notes should be well structured, detailed, and accurate to provide maximum value.

The Royal School of Mines maintains a field notebook standard format as an ideal example of excellent practice that ensures notes are high quality. These form a series of guidelines, as described below. An example is shown in Figure A1.

A.1 Structure of field notes

Field notebooks require a rigorous structure and consistent layout to ensure the information contained in the notes is easily accessible. The reason for taking notes in the field is to perform later analysis of the data. Making localities easy to find and sufficiently separate from each other is thus important.

Individual locality notes should also be structured with information recorded consistently throughout a notebook. Although every locality is different there are many common features, such as position, exposure type, and lithology, that need to be recorded and a consistent format ensures this information is easy to extract. Structure in locality notes also helps ensure good observation by providing a checklist of features to be described at each outcrop. Sub-dividing notes for each locality with underlined headings helps both accessibility and ensures a minimum standard of data recording. The titles used can vary but should include important features such as the nature of the exposure, the lithology, and the structures.

Interpretation should be separated from observation within a notebook and presented in a separate section within locality notes. Mineral and rock type identifications are not, however, considered interpretations. Every locality need not have a lengthy interpretation section.

Measurements are particularly important to record. Bedding, cleavage, and fold axial planes/plunges should all be taken where possible and recorded in the margins of a notebook using proper symbols. Bearings such as dip direction and strike are recorded as three digits whilst dip uses two digits (e.g. dip/direction 52/090 strike/dip 090/52). At the Royal School of Mines we use dip and dip direction since there is less chance to misinterpret or misrecord the dip direction.

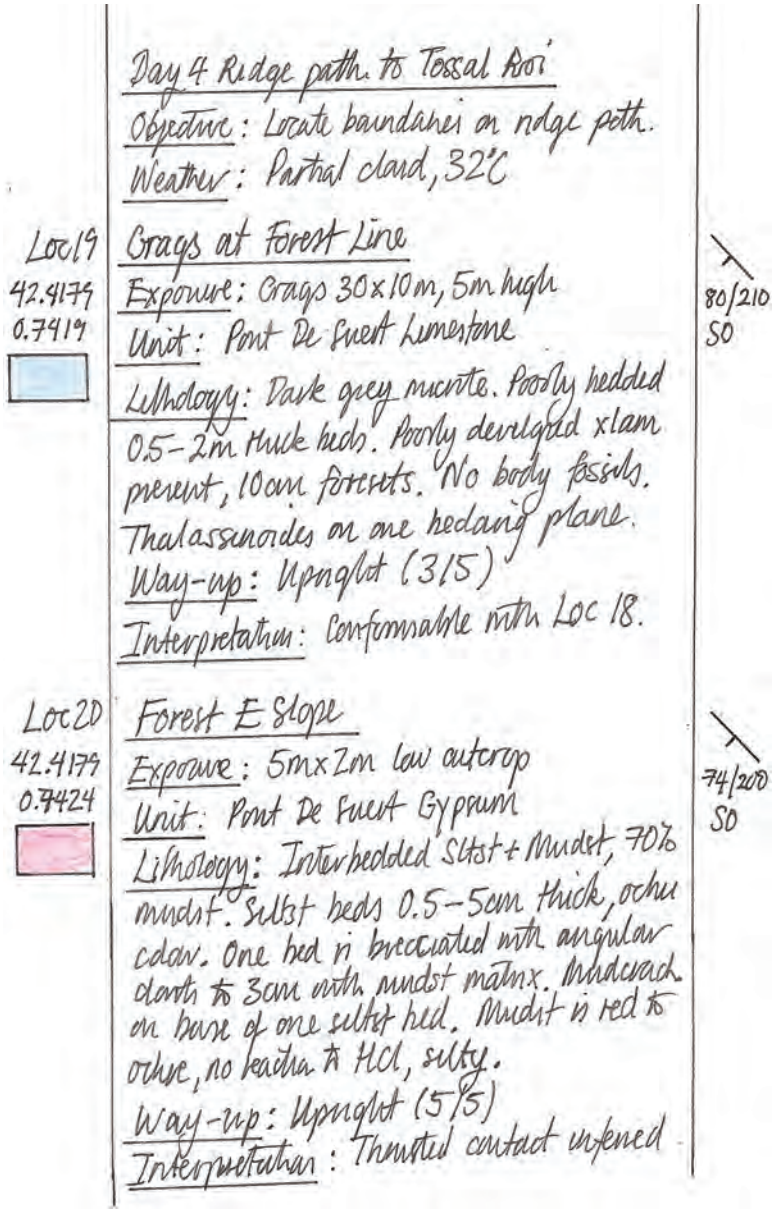

Day 4 Ridge path to Tossal Aoi
Objective: Locate boundaries on ridge path.
Weather: Partial cloud, 32°C
Loc 19
Crags at Forest Line
42.4179
0.7419
Exposure: Crags 30x10m, 5m high
Unit: Pont De Suert Limestone
Lithology: Dark grey micrite. Poorly bedded 0.5–2m thick beds. Poorly developed xlam present, 10cm forests. No body fossils. Thalassinoides on one bedding plane.
Way-up: Upright (315)
Interpretation: Conformable with Loc 18.
80/210
SO
Loc 20
Forest E Slope
42.4179
0.7424
Exposure: 5mx2m low outcrop
Unit: Pont De Suert Gypsum
Lithology: Interbedded Sltst + Mudst, 70% mudst. Sltst beds 0.5–5cm thick, ochre colour. One bed is brecciated with angular clasts to 3cm with mudst matrix. Mudcrack on base of one sltst bed. Mudst is red to ochre, no reaction to HCl, silty.
Way-up: Upright (5/5)
Interpretation: Thrusted contact inferred
74/200
SO

Figure A1 An example of well-structured detailed field notes. Two localities are shown, neither of which have many significant features. Some localities may involve several pages of notes and field sketches.

Notes can be written in ink in the field when the weather allows. Handwriting should be legible to others and neither excessively large or small.

A.1.1 Notebook structure

- Include a prominent header page for each fieldtrip giving location, objective, and dates.
- Begin each day's notes with a title, objective for the day's fieldwork, general location, and objective. Weather can also be recorded since conditions can affect the observations made.
- Separate each locality using a prominent heading.
- Use page numbers and record new days and significant localities in an index.

A.1.2 Locality note structure

- Separate two ruled margins on either side of the page approximately 1 cm wide. The left margin is used to record locality numbers and their grid references. The right margin is used to record measurements using an oriented symbol and numbers.
- Give your locality an underlined title to separate it from other localities.
- Use underlined sub-headings to record different categories of data. These include:
  - Exposure—always record the nature of the exposure, for example, road cutting, stream exposure, crags, sea cliffs. Record the size of the exposure in metres.
  - Use titles such as Lithology, Fossils, and Structure to sub-divide your descriptive locality notes.
  - Separate interpretation from observation by adding an interpretation section.
  - Field sketches should be included within locality notes.

A.1.3 Summaries

- Sections should be included in notebooks that summarize and interpret geology seen over more than one locality. These can summarize observations over one or more days or over an entire fieldtrip.

- Schematic diagrams, sketch cross-sections, and sketch maps are very useful in illustrating interpretation and in aiding the development of ideas.
- Ensure that summary sections are clearly titled to separate them from field observations (e.g. 'Summary of NW Valley').

A.2 Lithology notes

Lithology notes should use proper terminology and be as quantitative as possible. When several lithologies appear a general statement can be recorded to give context (e.g. 'Interbedded siltstones and mudstones (30:70%)'). Notes on each lithology can be recorded as a list of properties including rock type, nature and thickness of bedding, mineralogy/composition, grain sizes, grain shapes, sorting, and sedimentary structures. Using a consistent list of properties will ensure the proper information is recorded. Where possible include quantitative sizes and abundance estimates. Where complicated stratigraphic relationships are present sketch logs are useful to record lithology information with much of the detail recorded in the description column of the log.

Data on fossil assemblage and preservation can be given in lithology notes depending on the nature of the study. Where the objectives are palaeontology specific, or exceptional quality specimens are present, a separate section for fossils can be useful.

An assessment of the stratigraphic identity of the unit should be made where possible, even if associated with some uncertainty. When mapping, it is useful to record this information in the left-hand margin as a box containing the chosen colour for the formation. A confidence level out of five can be given to represent uncertainty (e.g. 3/5).

It is acceptable to use abbreviations in field notes; however, a legend describing the abbreviations should be given somewhere in the notebook.

Record any samples collected using a unique sample number. Note whether photographs were taken.

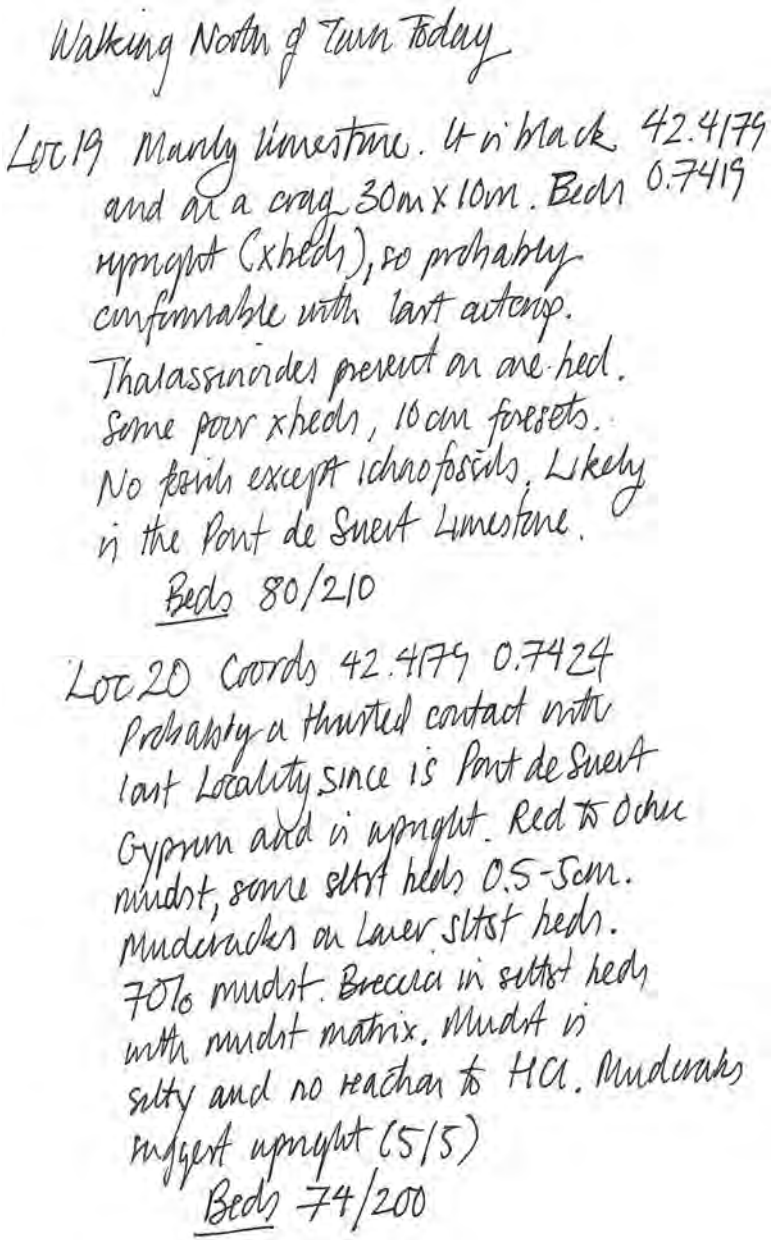
A.3 Structure notes

Field notes on tectonic structures should describe the geometry, size, and orientation of structures. In the case of faults, the type and displacement should also be given where possible. Measurements of structures, such as fold axial planes, cleavage planes, fold hinges, and other lineations, should be added to the right-hand margin of the notebook as oriented symbols. The way-up of beds is also important to record under structure. An indication of the degree of uncertainty in measurements should be given.

Field sketches are the best way to record the nature of structures and should be appropriately annotated. Use proper notation for different generations of structure (e.g. S0 for bedding, S1 for slaty cleavage, S2 or above for crenulation cleavage).

A.4 Common mistakes

The commonest mistakes made in notebooks are poor structure and insufficient detail in descriptions. An example of notes with poor structure is shown in Figure A2. The localities in these notes are insufficiently separated from each other and there is no consistent order in how information is recorded at each locality. Poor structure leads to the omission of important observations. An example of notes with insufficient detail is given in Figure A3. These notes feature some poor terminology and few quantitative measurements/estimates. Interpretation is also mixed together with observation.


Walking North of Town Today

Loc 19 Marly limestone. Lt grey black. 42.4179
and at a crag 30m x 10m. Beds 0.7419
upright (x beds), so probably
conformable with last outcrop.
Thalassinoides present on one bed.
Some poor x beds, 10 cm foresets.
No fossils except ichnofossils. Likely
is the Pont de Suert Limestone.
Beds 80/210

Loc 20 Coords 42.4179 0.7424
Probably a thrusted contact with
last Locality since is Pont de Suert
Gypsum and is upright. Red to Ochre
mudst, some siltst beds 0.5-5cm.
Mudcracks on Lower siltst beds.
70% mudst. Breccia in siltst beds
with mudst matrix. Mudst is
salty and no reaction to HCl. Mudcracks
suggest upright (5/5)
Beds 74/200

Figure A2 An example of poorly structured field notes. The two localities described here are the same as in Figure A1 and include the same information. Poor structure and mixing of interpretation and observation make these notes inaccessible.

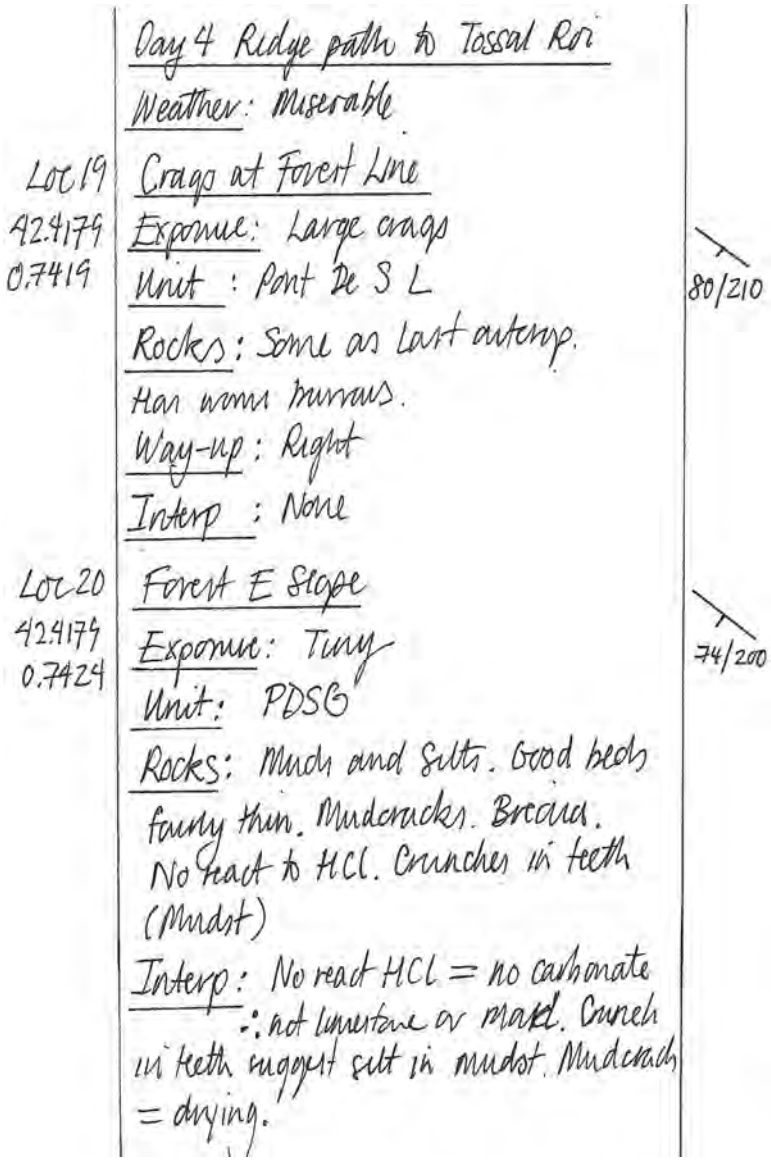


Figure A3 An example of notes with insufficient quantitative detail and poor terminology. The two localities described here are the same as in Figure A1 but fail to record much of the important information. Interpretations in the notes focus on minor factors that could be considered fundamental knowledge rather than interpretation of rock-forming processes.

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